Subaru Telescope
National Astronomical Observatory of Japan

Semester	S05B
Proposal ID	S05B-
Received	/ /

Application Form for Telescope Time

1. Title of Proposal

Dark Energy Measurements using SNIa in Elliptical Galaxies

2. Principal Investigator

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3. Scientific Category

- [ ] Solar System
- [ ] Normal Stars
- [ ] Extrasolar Planets
- [ ] Star and Planet Formation
- [ ] Compact Objects and SNe
- [ ] Milky Way
- [ ] Local Group
- [ ] ISM
- [ ] Nearby Galaxies
- [ ] Starburst Galaxies
- [ ] AGN and QSO Activity
- [ ] QSO Absorption Lines and IGM
- [ ] Clusters of Galaxies
- [ ] Gravitational Lenses
- [ ] High-z Galaxies
- [ ] Deep Surveys
- [ ] Large-Scale Structure
- [⋆] Cosmological Parameters
- [ ] Miscellaneous

4. Abstract *(approximately 200 words)*

We propose to perform the ground-based component of an approved major 219–orbit HST program which uses a new approach to measure cosmological expansions with "dust free" Type Ia supernovae (SNe Ia). By targeting massive galaxy clusters at z$\gtrsim$ 1 we obtain a five-times higher efficiency in detection of SNe Ia in ellipticals, providing a well-understood host galaxy environment. HST/ACS repeated imaging will give $\sim$ 30 SN light curves, among which we expect $\sim$ 10 SNe Ia in elliptical hosts. Subaru/FOCAS superb image quality enables us to carry out deep spectroscopy of SN candidates and hosts to give their SN types and redshifts. The expected SN data set will make possible a factor of two improvement on supernova constraints on dark energy time variation, and much larger improvement in systematic uncertainty. We will also carry out follow-up spectroscopy of host galaxies of 10 SNe found with Suprime-Cam in order to put their light curves on SNIa Hubble diagram at redshifts z$\gtrsim$ 1.

5. Co-Investigators

Name	Institute	Name	Institute
Naoki Yasuda	University of Tokyo	Naohiro Takanashi	University of Tokyo
Tomonori Totani	Kyoto University	Koichi Tokita	University of Tokyo
Nobunari Kashikawa	NAOJ	Takashi Ihara	University of Tokyo
Hisanor Furusawa	NAOJ	Saul Perlmutter	LBNL
Tomoki Morokuma	University of Tokyo	Chris Lidman	ESO

6. List of Applicants' Related Publications *(last 5 years)*

Lidman,C. et al., 2005, A&A, 430, 843, "Spectroscopic confirmation of high-redshift supernovae with the ESO VLT"
Tegmark,M. et al. 2004, PhRvD, 69,10,103501 "Cosmological parameters from SDSS and WMAP"
Doi, et al., 2003, IAUC, 8120, "Supernovae 2002km-2002ky"
Knop, R. A. et al., 2003, ApJ, 598, 102, "New Constraints on Omega$_M$, Omega$_\Lambda$, and w from an Independent Set of 11 High-Redshift Supernovae Observed with the Hubble Space Telescope"
Sullivan, M. et al., 2003, MNRAS, 340, 1057, "The Hubble diagram of type Ia supernovae as a function of host galaxy morphology"
Yasuda, N. et al. 2003, *Very High Redshift Supernova Discoveries with Subaru/Suprime-Cam*, AAS, 203.8211Y
Yasuda, N. et al. 2002, *Supernovae 2002fc, 2002fd, 2002fe, 2002ff, 2002fg, 2002fh*, IAUC 7971
Miyazaki, S. et al., 2002, PASJ, 54, 833 "Subaru Prime Focus Camera – Suprime-Cam"
Doi,M. et al., 2001, IAUC, 7649, "Supernovae 2001cq, 2001cr, 2001cs, 2001ct, 2001cu, 2001cv, 2001cw"

 Proposal ID S05B-

Pages 2 and 3 will be used for technical review by observatory staff. Please provide here clear and detailed information for these purposes. The entire proposal including scientific justification will be passed to support astronomers for preparation of observations upon acceptance.

7. Title of Proposal

Dark Energy Measurements using SNIa in Elliptical Galaxies

8. Observing Run **Too many nights requested!**

Instrument	# Nights	Moon	Preferred Dates	Acceptable Dates	Observing Modes
FOCAS	10	Gray	Sep–Jun	Sep–Jun	grism

Total Requested Number of Nights: 10 — Minimum Acceptable Number of Nights: 5

9. List of Targets *(Use an additional sheet if this space is not sufficient)*

☐ I do **not** want observatory staff to see the target names for the technical review.

Target Name	RA	Dec	Equinox	Magnitude (Band)

10. Scheduling Requirements ☐ *Request Remote Observation*

We request 1 night every month or two nights every other month, depending on the telescope schedule. HST/ACS search observations will be allocated from Sep.2005 to June 2006. Since we have to coordinate HST observations, it is very (extremely) important to contact us to coordinate with the HST schedule before fixing the Subaru schedule. "Dark" nights are favarable since our targets are very faint, although "Grey" nights are acceptable if necessary.

11. Instrument Requirements

12. Experience

We have enough experiences of using FOCAS, and successfully obtained faint SN spectra since 2001.

13. Backup Proposal in Poor Conditions *(specify object names)*

Under poor conditions we will do spectroscopy of bright SNe in the same field.

14. Observing Method and Technical Details

Please describe in detail about instrument configuration, exposure time, required sensitivity, and so on.

We use 300B grating with SY47 order-cut filter ($z \lesssim 1$) or 300R grating with SO58 ($z \gtrsim 1$). We use a long slit of the width of 0.8 arcsec as the default, although we will change the slit width depending on seeing. We will have default binning of 2 by 2, although we will change binning parameters depending on seeing and target magnitude.
Our previous experiences show that 2.5 – 3 hours (including overhead) can go deep enough to obtain the necessary S/N for SNe at $z \sim 1$, and we spend more if the target is really promising and fainter.
HST/ACS SN searches will give us ~3 SN candidates per month, and ~1 SN candidate in an elliptical host galaxy. We will typically observe 2 of these per month, requiring 6 hours. We also require spectra of 10 host galaxies of SNe Ia whose redshifts are unknown, for which we already have Subaru/Suprime-Cam lightcurves that indicate z$\gtrsim$1. We will typically observe 1 of these per month on average, requiring an additional 3 hours. Thus, in total we propose to observe 3 candidates per month with Subaru/FOCAS spectroscopy. Therefore we request a total of 10 nights from Sep.2005 to June 2006.
MOS option to carry out spectroscopy of surrounding galaxies is preferable for cluster sciences, and we would like to choose it if allowed. But priority of this request is low.

15. Condition of Closely-Related Past Observations

Please fill in here, if this proposal is a continuation of (or inextricably related with) the previously accepted proposals. This is to describe what kind of relevant/similar proposals have existed in the past and how such previous observations were carried out.

Proposal ID	Title (may be abbreviated)	Observational condition	Achievement (%)

16. Post-Observation Status and Publications

Please report the status or outcome of your main Subaru observations carried out in the past. All observations relevant to this proposal (e.g., those enumerated in the above entry 15) must be included here; otherwise, only those within last 3 years suffice.

Year/Month	Proposal ID	PI name	Status: data reduction/analysis	Status: publication
04/03	S03B-227	M.Doi	completed	in preparation
02/11	S02B-IP-04	M.Doi	completed	published in part
02/04	S02A-174	M.Doi	completed	published in part
02/04	S02A-174	M.Doi	completed	published in part

17. Thesis Work

☐ This proposal is linked to the thesis preparation of ______________________

18. Subaru Open Use Intensive Programs

[⋆] This is a proposal for Intensive Programs.

19. List of Targets

☐ I do **not** want observatory staff to see the target names for the technical review.

Target Name	RA	Dec	Equinox	Magnitude (Band)
SuF02-007	02 18 52.4	-05 01 14	J2000.0	$i = 25$
SuF02-012	02 18 51.6	-04 47 26	J2000.0	$i = 24.7$
SuF02-026	02 18 51.9	-04 46 57	J2000.0	$i = 23.2$
SuF02-034	02 18 31.2	-05 01 25	J2000.0	$i = 24.2$
SuF02-051	02 17 27.5	-04 40 45	J2000.0	$i = 25$
SuF02-056	02 20 00.0	-04 44 21	J2000.0	$i = 23.3$
SuF02-057	02 20 13.9	-05 07 36	J2000.0	$i = 25$
SuF02-058	02 17 59.7	-04 52 27	J2000.0	$i = 22.9$
SuF02-J02	02 18 42.9	-05 04 12	J2000.0	$i = 22.3$
SXDS-1-b	02 17 09.7	-04 57 48	J2000.0	$i = 24.4$
1012.28	14 34 16.0000	+34 26 0.00	J2000.0	$i = 24.5$
1012.52	14 32 43.0000	+33 32 0.00	J2000.0	$i = 24.5$
1214.18	14 28 37.0000	+34 29 0.00	J2000.0	$i = 24.5$
1214.19	14 34 52.0000	+34 25 0.00	J2000.0	$i = 24.5$
1214.30	14 35 26.0000	+33 06 0.00	J2000.0	$i = 24.5$
1315.12	14 34 58.0000	+35 19 0.00	J2000.0	$i = 24.5$
1416.21	14 32 8.0000	+32 37 0.00	J2000.0	$i = 24.5$
1517.1	14 30 48.0000	+32 32 0.00	J2000.0	$i = 24.5$
CL1604+43	16 04 0.0000	+43 04 0.00	J2000.0	$i = 24.5$
RCS0220-03	02 20 42.0000	-03 33 0.00	J2000.0	$i = 24.5$
RCS0221-03	02 21 54.0000	-03 22 0.00	J2000.0	$i = 24.5$
RCS0337-28	03 37 30.0000	-28 45 0.00	J2000.0	$i = 24.5$
RCS0439-29	04 39 48.0000	-29 00 0.00	J2000.0	$i = 24.5$
RCS1329+30	13 29 0.0000	+30 19 0.00	J2000.0	$i = 24.5$
RCS1416+53	14 16 40.0000	+53 05 0.00	J2000.0	$i = 24.5$
RCS2156-04	21 56 0.0000	-04 00 0.00	J2000.0	$i = 24.5$
RCS2319+00	23 19 36.0000	+00 00 0.00	J2000.0	$i = 24.5$
RDCS0848+44	08 48 48.0000	+44 53 0.00	J2000.0	$i = 24.5$
RDCS0910+54	09 20 0.0000	+54 22 0.00	J2000.0	$i = 24.5$
RDCS1252-29	12 52 42.0000	-29 27 0.00	J2000.0	$i = 24.5$
XMM33	22 35 0.0000	-25 57 0.00	J2000.0	$i = 24.5$

Dark Energy Measurements using SNIa in Elliptical Galaxies. M. Doi *et al.*

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

We have been awarded one of the largest–ever HST programs (219 orbits) to use a new approach to the measurements in this difficult decelerating redshift range. By studying "clean" SNe discovered specifically in galaxy-cluster ellipticals, we can remove this primary statistical and systematic uncertainty. This Subaru proposal is for the crucial ground-based component of this project: the spectroscopy.

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

The correction for the extinction of SNe from dust in the host galaxies is currently the single dominant source of both statistical and systematic error for SNe distances and the derived cosmological parameters – dramatically so at $z > 1$ (see Figure 1b).

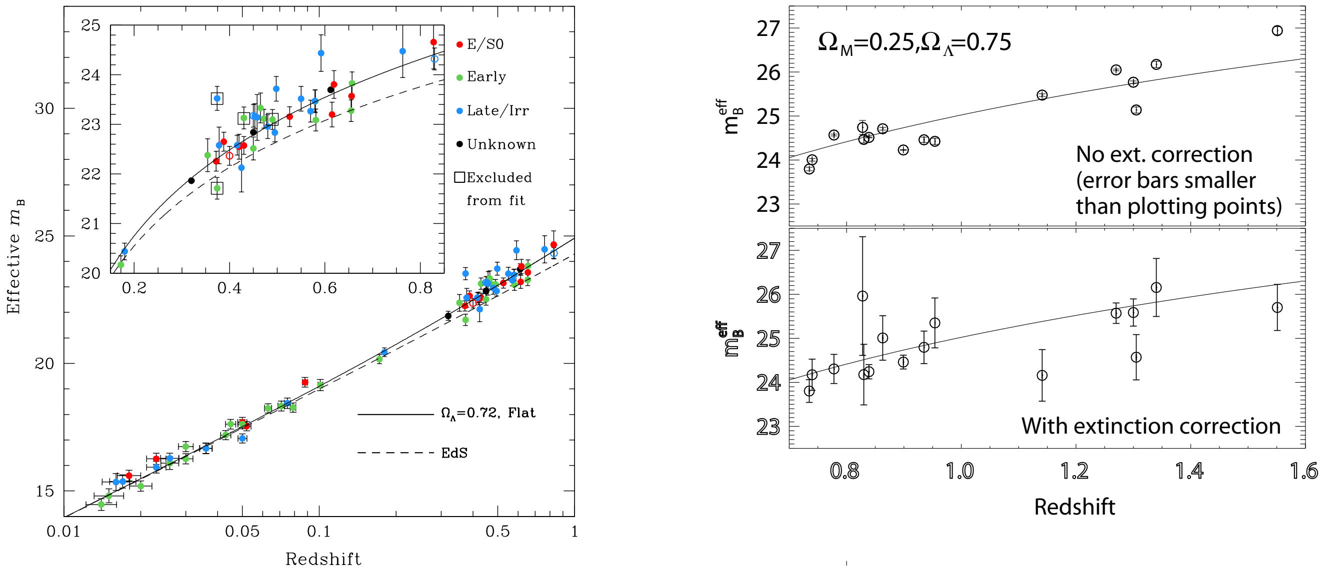

Figure 1 (a) Left Panel: The SCP SN Ia Hubble diagram broken into host galaxy types from Sullivan *et al.* (2003). The SNe in elliptical hosts (filled red circles) show significantly less dispersion, $\sigma = 0.16$ mag, including measurement error. (This ground-based measurement error for this $z \sim 0.5$ sample is quite close to the HST measurement error at $z > 1$ in this proposal.) **(b) Right Panel:** The comparison of the Hubble diagram, before and after extinction correction, for a mixture of SNe Ia in all host types shows the dramatic increase in error bars due to the uncertainty in $B - V$ color being multiplied by $R_B \approx 4$ and by the uncertainty in R_B. The data shown is from the SCP (Knop *et al.* 2003) and the Riess et al. 2004 GOODS search samples. For the SNe at redshifts $z > 1$ this yields an uncertainty of ∼0.5 mag, which is consistent with the measured dispersion of 0.5 mag. The ratio of this dispersion to the elliptical-hosted dispersion of panel (a) makes the elliptical-hosted SNe each worth 9 of the extinction-corrected others.

The typical color uncertainties for $z > 1$ SNe is $0.08 - 0.1$ in $B - V$, leading to uncertainties in extinction correction (after accounting for intrinsic color uncertainty) of >0.4 mag! This dispersion grows worse, $\sigma \approx 0.5$, after accounting for the uncertainty in the dust reddening coefficient, $R_B \equiv A_B/E(B-V)$, which Draine (2003) notes can vary from the fiducial value 4.1 by ±0.5. Recent studies of nearby SNe Ia (Altavilla *et al.* 2004, Reindl *et al.* 2005) are consistent with large dispersions of R_B. (Note that the actual dispersion about the Hubble-line fit for $z > 1$ SNe Ia corrected for extinction matches this 0.5 mag value.)

These large dispersions in extinction correction have been dealt with, e.g. in Riess *et al.* (2004), by applying a strong Bayesian prior to the distribution, assuming knowledge of the dust and SN distribution in the $z > 1$ host galaxies (shaded contour of Fig. 2b). However, such Bayesian priors are necessarily one-sided (no negative reddening) and hence are known to introduce systematic biases when the error bars are larger at high-redshift than low-redshift (Perlmutter *et al.* 1999). This bias can be seen in Fig. 2b as the difference between the long-dashed contour and the solid contour. This approach to the extinction analysis is also subject to other obvious sources of systematic biases, for example if the mean value of R_B drifts from low to high redshift, as shown by the short-dashed contour of Fig. 2b.

How is this problem solved using SNe Ia in ellipticals?

In Sullivan *et al.* (2003), we showed that the dispersion (including ground-based measurement error) about the Hubble diagram for elliptical-hosted SNe is 0.16 mag — three times smaller than just the measurement uncertainty for extinction-corrected SNe Ia at $z > 1$ — primarily due to the absence of dust. Thus, SNe Ia in ellipticals are statistically each worth *nine times* that of SNe in spirals when making cosmological measurements – and without the aforementioned systematics associated with extinction correction. We therefore propose to collect a sample of ∼10 SNe Ia at $z \gtrsim 1$ entirely in cluster elliptical host galaxies, to achieve the statistical constraints of ∼90 SNe in later-type hosts. (This sample's statistical strength is thus a good match for the comparison and systematics studies of the past and ongoing HST/GOODS-searches' non-elliptical sample.) This proposed ellipticals-only sample would yield the stronger constraints on w vs. w' shown in Fig. 2c — without extinction prior systematics. In particular, this would provide a test of the small, suggestive shift from a cosmological constant model seen in Riess et al 2004 (Fig. 2b shaded contour). Note that the $z = 0.9 - 1.6$ redshift range provides key leverage of the cosmological model, especially constraints on the dark energy time variation w'.

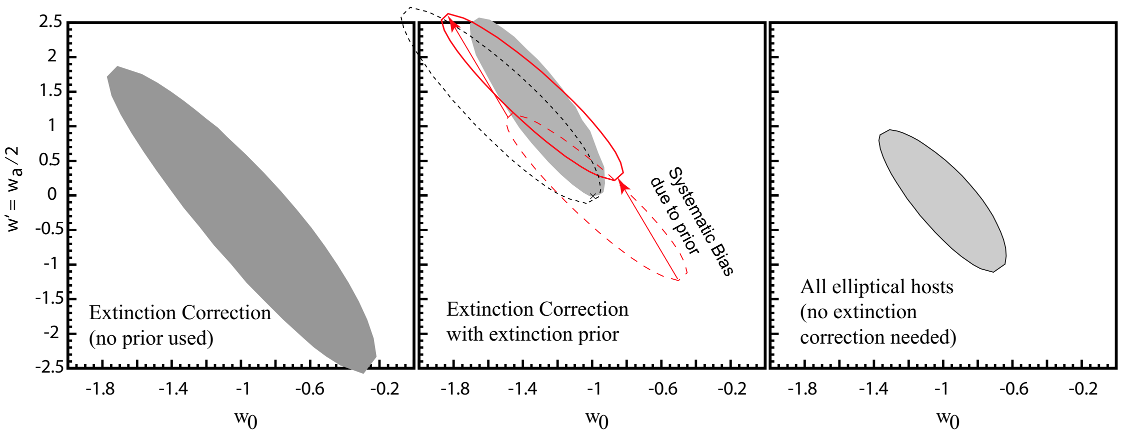

Figure 2 (a) Left Panel: Simulated 68% confidence region on w' vs w_0 for the current literature SN sample but with underlying cosmology ($w_0 = -1$; $w' = 0$). The parameters are poorly constrained because color errors are magnified by $R_B \approx 4$. **(b) Middle Panel:** The solid red contour shows reduced uncertainties (excluding systematic bias) using a Baysian prior on the extinction distribution prior to suppress color errors. If the errors are larger at high z than at low z (as with the actual data), this introduces systematic biases. The filled gray contour is from Riess *et al.* 2004 using this prior. The short-dashed contour shows that this approach is also sensitive to shifts in R_B with redshift; the example shifts from 4.1 to 2.6. **(c) Right Panel:** The goal of this proposal is shown as a confidence region for a simulated new sample of ~ 10 $z \gtrsim 1$ SNe Ia found in cluster ellipticals, together with 5 in ellipticals from the past and ongoing GOODS searches, as well as 120 SNe Ia in ellipticals at the lower redshifts now being produced by the ground-based CFHT SN Legacy Survey, the CTIO Essence survey, and (at $z < 0.1$) the Nearby SN Factory. A SN Hubble diagram in ellipticals avoids the large statistical error problem of panel (a) and the large systematics problem of panel (b).

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

Although evidence for dust is found in about 50% of nearby elliptical galaxies, the quantity of dust is generally very small and confined to a central disk where its cross-section is very small. The clearest line of evidence that dust has little effect on stars in elliptical galaxies comes from the tightness of the color-magnitude relation. The dispersion in the colors of early-type galaxies has long been known to be very small in clusters ranging from Coma to intermediate redshifts (Bower *et al.* 1992; Ellis *et al.* 1997; Stanford, Eisenhardt & Dickinson 1998; van Dokkum *et al.* 2001; Blakeslee *et al.* 2003, Nakata *et al.* 2005). Recent results from HST imaging show the same strikingly small dispersion in color extends to redshifts $z \gtrsim 1$.

HST/ACS observations

There are number of systematic surveys of SNIa for nearby and intermediate redshifts (e.g. SDSS-II, SN Factory, ESSENSE, SNLS) which will give such "clean" SNIa sample eventually. But in order to measure the cosmological expansion over last 10Gyears, we need deeper observations.

In order to find SNe Ia in elliptical hosts at $z \gtrsim 1$, we were awareded 219 orbits of HST/ACS telescope time in cycle 14 (July 2005 – June 2006). We proposed repeated photometry (F850LP) of 22 clusters of galaxies ($0.9 < z < 1.5$) with HST/NICMOS2 followup photometry (F110W). HST/ACS is the best instrument since these observations will also give us resolved host morphology as well as deep SN light curves. The requested 219 orbits are fully awarded (note that this is one of the largest programs in HST proposals). We will discover ∼30 SNe among which ∼10 SNe Ia in elliptical hosts are expected. Fig.3 shows how light curves will be continuously observed based on simulated data for the HST program, providing good targets for spectroscopy every month.

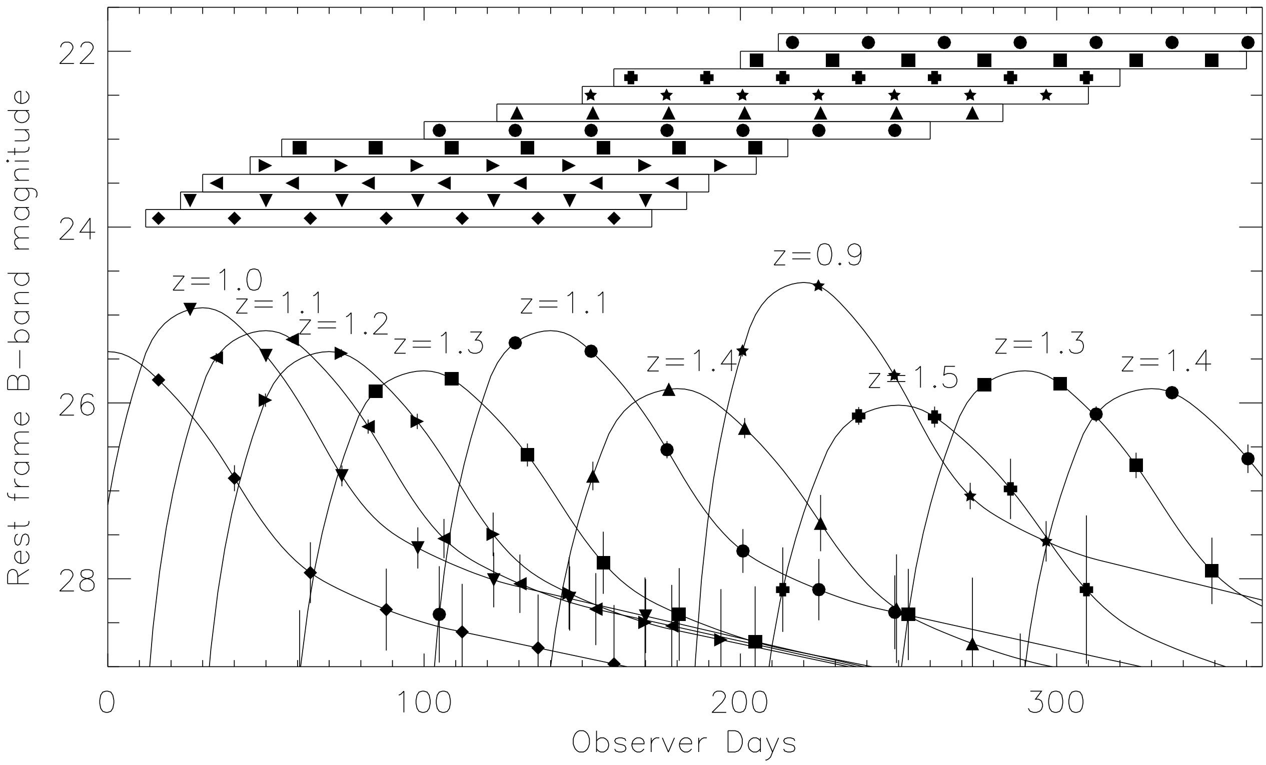

Figure 3 The simulated HST data set for this proposal, with signal-to-noise at a given redshift and SN epoch based on our previous SN from HST/ACS and HST/NICMOS. The simulated data was fit with our lightcurve analysis program to test the cadence feasibility. We obtain typical errors of 0.07 to 0.13 mag for $0.9 < z < 1.5$, including the lightcurve timescale stretch correction uncertainty. The bars and symbols at top show the observing time period and scheduled observations for each cluster (with different cadences depending on the cluster z). The same symbols are used for the observations on the lightcurves, to show where a SN might be discovered and followed in its cluster's time window. Note that the observations are well spread throughout the year (allowing easy HST scheduling, with flexibility since there are other clusters to study if one is difficult to schedule). There are therefore SNe to be observed in this proposed Subaru observing program at almost any time, in addition to the host galaxies that can be observed any time.

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

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

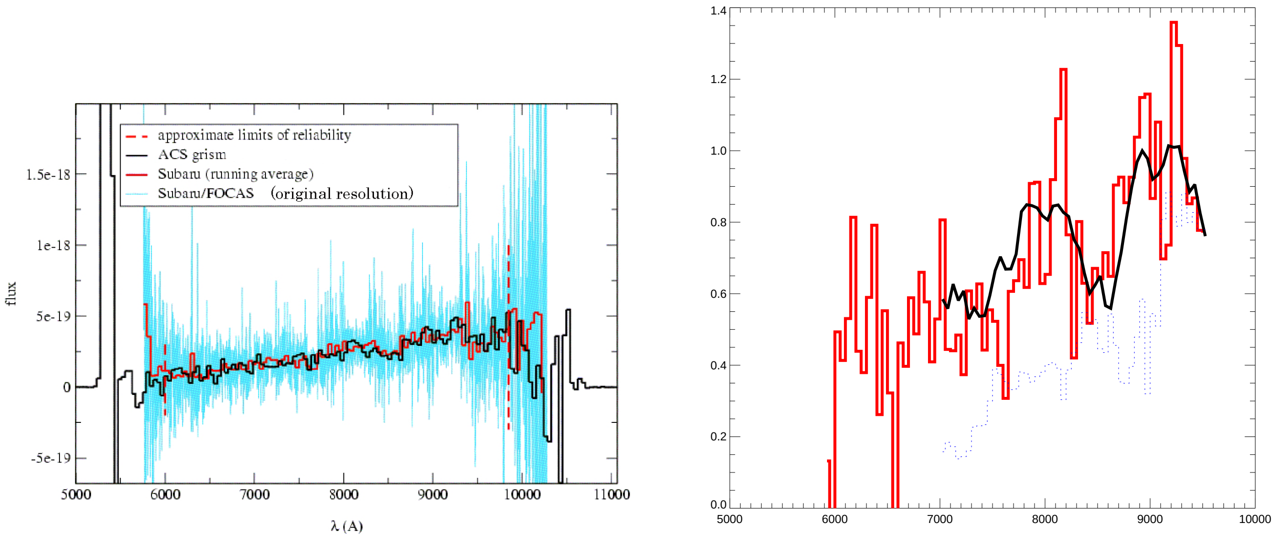

Figure 4 (a) Left Panel Comparisons of spectra of SN2002lc ($z \sim 1.28$) which was found with Suprime-Cam rolling searches (S02B-IP-04). The black line shows a spectrum of SN2002lc taken with HST/ACS G800L grism observations with $\sim$ 12000 sec exposures. The blue line shows a spectrum of the same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

Additional observations to follow SNe found with Suprime-Cam

In addition to follow-up spectrosopy of precious "dust free" SNe Ia, we also propose taking spectra of host galaxies of SNe which were found with Suprime-Cam. Fig.5 shows light curves and a preliminary Hubble diagram of 2002 Fall SXDS rolling searches (S02B-IP-04). Blue circles are SNe Ia with spectroscopic redshifts, while red circles are possible SNe Ia with unknown redshfts. As is compared in the figure, there are not many data points at high redshift yet. And we can almost double the number of data points at $z \gtrsim 0.9$ if we measure all redshifts of SNe in red circles.

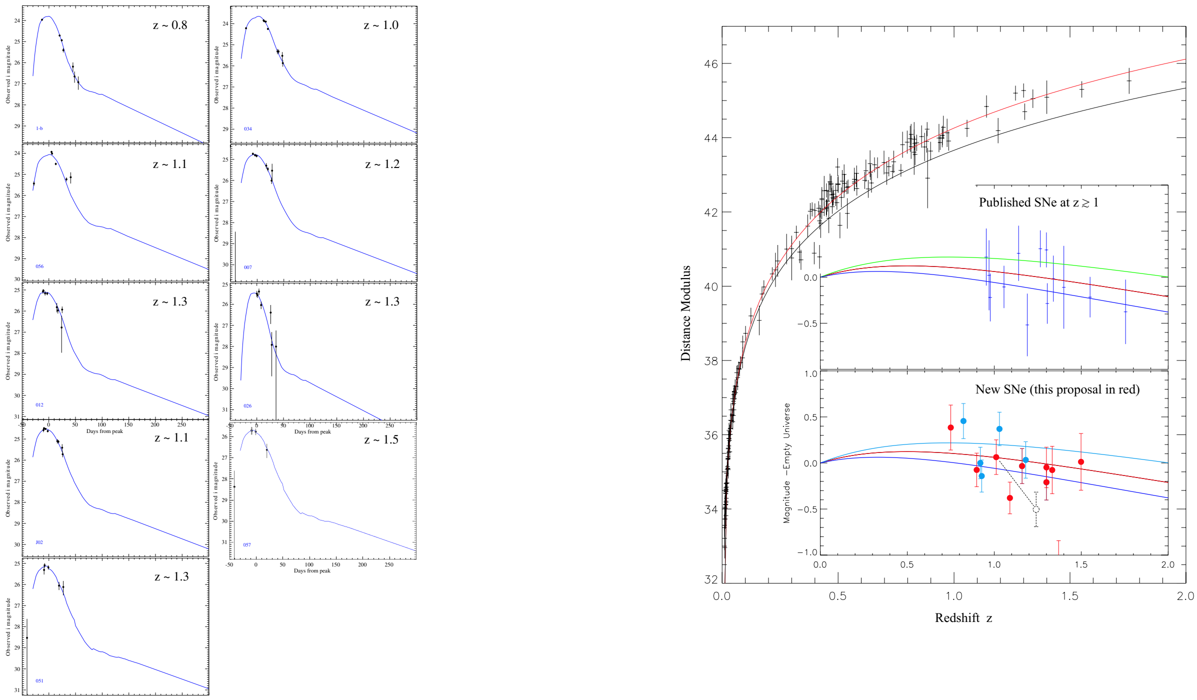

Figure 5 (a) Left Panel: The i′-band lightcurves for the nine supernovae targeted by this proposal. The light curves here were taken with Suprime-Cam (S02B-IP-04), and each of these SNe also has R- and z′-band photometry points near maximum light (not shown). Note that for these nine SNe the integrated host galaxy light in a 1″ aperture is significantly brighter than the SN in almost every case. **(b) Right Panel:** The Hubble plot for SN Ia, based on a compilation of SNe in the literature discovered primarily by both the Supernova Cosmology Project and the High-Z SN Search (Riess et al. 2004). The solid curves show flat cosmologies with $\Omega_M = 0.3$ (top) and 1.0 (bottom). At the highest redshifts – in the epoch of deceleration – the plot is very sparsely populated. *Upper Inset:* The magnitude residual from an empty universe ($\Omega_M = \Omega_\Lambda = 0$) for the SNe from this compilation at the highest redshifts. The solid curves show flat cosmologies with $\Omega_M = 0.2$, 0.3, and 0.4 (top to bottom). *Lower Inset:* The magnitude residual from an empty universe for the new SNe discovered in our Subaru-based search (S02B-IP-04) for SNe at these decelerating redshifts. The SN indicated by blue points have spectroscopically measured redshifts, while those indicated with red points are plotted using *approximate* redshifts estimated from the time-dilation of the lightcurve timescale. The dashed-line point shows the $\sim 1\sigma$ range of variation of this redshift estimate, *assuming* the known dispersion of lightcurve timescales (from Perlmutter et al. 1999 and Knop et al. 2003). (This dashed-line point is at the same magnitude as its corresponding solid-line point, but the different assumed redshift gives a very different residual from the empty universe.) We here propose to obtain the exact spectroscopic redshift for the host galaxies of each of these SNe.

Conclusions

The spectroscopy observations proposed here are the key gound-based component of a very large approved HST program using known approach to SN measurements which will provide a first significant, *and unbiased* measurement of w_0 vs. w'. The emphasis on high redshift and attention to systematics are the opening steps in bringing to maturity cosmological methods of the next generation, and this program will serve as a bedrock scientific legacy for dark energy studies.

References

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