A Sparse Spectroscopic Supernova Survey

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Supernova cosmology surveys are traditionally time consuming, especially for the critical spectroscopic data. However, a single spectrum at maximum light may provide accurate distance estimation if recent developments hold. This could open up a new type of supernova cosmology survey, with a useful interaction between the spectra and a focus on specific redshifts. We optimize the redshift selection and show that this condensed survey could efficiently deliver highly accurate dark energy constraints.

I. INTRODUCTION

Supernovae type Ia (SN) are the most incisive dark energy probes, with a better sensitivity to dark energy equation of state properties with respect to matter density than other measurements. Their distance-redshift relation relies predominantly on individual object measurements, substantially avoiding systematics issues such as survey inhomogeneity (masking and depth variations), source blending (SN are transients and have a unique spectrum), image distortion from atmosphere/telescope/detector, etc. SN do have their own systematics, but many of these can be avoided by detailed spectrophotometric measurement rather than a purely imaging survey.

A significant recent development has been the improvement of SN distance calibration through detailed spectral information [1, 2]. Moreover, this enables an important advance in obtaining this information from only a single spectrum measurement at an epoch near maximum light. This would decrease the observational expense of obtaining high accuracy SN distances, while reducing both statistical dispersion and systematics uncertainty.

If this promise holds, it could enable a revolution in the approach to supernova cosmology. A corollary impact could be in the cosmic survey design, to make it even more efficient. While traditionally one measures SN distances over a continuous redshift range, e.g. $z = [0, 1]$, the kernel for cosmological parameter sensitivity is broad enough that a sparse survey in selected redshift slices could deliver quite accurate constraints. The interaction between the redshift and the observer frame wavelength of SN spectra could also simplify the instrumentation as they can imply specific wavelength ranges of interest.

Section II introduces the method for computing the optimal redshift slices and evaluates the impact on the cosmological constraints. In Section III we discuss some of the ingredients necessary for enabling such a survey, in particular ground-space complementarity. We conclude in Section IV.
of this in Section III but first assess its possible implications.

The leverage on dark energy properties can be compactly discussed in terms of the figure of merit,

\[ \text{FOM} \equiv 1/\sqrt{\det(COV(w_0, w_a))}, \]

where \( COV \) is the inverse of the information matrix, marginalized over the other cosmological parameters, and we include a Planck prior on the distance to the cosmic microwave background distance to last scattering. For maximal leverage and breaking of covariances between parameters, the SN survey should make measurements at the lowest and highest redshifts available, but not necessarily all those in between. We set \( z_{\text{low}} = 0.05 \) and \( z_{\text{max}} = 1 \), later considering variation of \( z_{\text{max}} \). To maximize the efficiency of the survey, we want the minimum number of redshift slices (and hence wavelength regions), which is equal to the number of parameters being constrained, in this case four. Thus we have two free survey parameters, the redshift centers of slices \( z_2 \) and \( z_3 \). When observationally practical, such sparse redshift surveys can deliver tighter parameter estimation than covering the full range given resource constraints — see \([4-6]\) — and be highly efficient. Cosmologically, this works because the redshift kernel of distance sensitivity to cosmological parameters has a width of an appreciable fraction of the evolution, whether from an e-fold of expansion or other physical dynamics \([7]\).

We optimize \( z_2, z_3 \) to deliver a maximum FOM, i.e. the most incisive information on dark energy properties. For the measurement precision we take it to be limited by some residual systematics for a future high accuracy spectroscopic survey. We adopt the Linder-Huterer (LH) prescription \([8]\) for the form, using

\[ \frac{\delta d_{\text{sys}}}{d} = 0.0017(1 + z), \]

increasing with redshift. This 0.17%-0.34% accuracy is equivalent to 3.7 mmag at \( z = 0 \) to 7.4 mmag at \( z = 1 \) — certainly challenging, but we are aiming for a spectroscopic SN survey in the LSST era, using the recent machine learning “Twins Embedding” technique of \([1, 2]\) or future further improvements. Twins Embedding is not only powerful on systematics mitigation but reduces the dispersion remaining after the spectral fit, hence a systematics limited survey seems reasonable (see Section III for a more quantitative discussion). We later explore the impact of varying this level. The LH systematic is taken to be coherent over a redshift slice of width \( \Delta z = 0.1 \), so we impose \( z_3 \geq z_2 + 0.1 \).

Figure 1 shows the results for how the dark energy figure of merit varies over the \( z_2-z_3 \) plane. The optimum is at \( z_2 = 0.28, z_3 = 0.38 \) with maximum FOM=295. This is quite impressive, comparable to many other Stage 4 dark energy experiments, even those with multiple probes. Of course it depends on the ability to realize the tight systematics control.

The excellent FOM occurs despite the sparseness of the survey, using only four redshift slices (of width \( \Delta z \leq 0.1 \)) at \( z = 0.05, 0.28, 0.38, 1 \). The exact positions of the intermediate slices comes from an interplay between cosmological sensitivity and systematics; the power of an optimized sparse survey can be seen by noting that using five redshift slices (so roughly 25% more statistics) but more evenly spread at \( z = 0.05, 0.25, 0.5, 0.75, 1 \) would give less than a 2% improvement in FOM. Dark energy properties are constrained to \( \sigma(w_0) = 0.051, \sigma(w_a) = 0.23 \), and \( \sigma(\Omega_m) = 0.0055 \). This would be a significant advance in our knowledge of dark energy.

The low and high redshift limits of the SN survey are quite important. Raising the lowest slice to \( z_{\text{low}} = 0.1 \) would reduce the FOM by 28%. Lowering the highest slice to \( z_{\text{max}} = 0.9 \) reduces the FOM by 8%, while raising it to \( z_{\text{max}} = 1.1 \) increases the FOM by 6%. The systematics level also has significant impact: if we double its level then the FOM decreases by a factor 3.2, if we put a floor on the systematics of Eq. (3) of 5 mmag (0.23% in distance, effectively raising the systematics on the SN at \( z_{\text{low}} \) and \( z_2 \) to the level at \( z_3 \)) the FOM is reduced by 13%.
| Redshift | Wavelength (µm) | \(N_{\text{sys}}\) (0.101 mag) | \(N_{\text{sys}}\) (0.073 mag) | \(N_{\text{sys}}\) (0.02 mag) |
|----------|----------------|------------------|------------------|------------------|
| 0.05     | 0.28           | 675              | 353              | 27               |
| 0.38     | 0.92           | 454              | 238              | 18               |
| 1.0      | 0.99           | 391              | 204              | 16               |
| 1.44     | 1.44           | 186              | 98               | 8                |

TABLE I. The optimized \(S^4\) targets supernovae at four redshift slices, given by the first row, with the spectrum maximum wavelength in the observer frame given in the second row. The third through fifth rows show the number of SN required for statistical uncertainty to fall below the systematics goal, for three choices of the residual intrinsic dispersion.

### III. SURVEY CONSIDERATIONS

The previous section sets an impactful goal that future surveys can strive to achieve. As mentioned, one promising approach comes from the results of [1, 2] that find that a single spectrum near maximum light can serve as an accurate SN distance indicator. They also raise the intriguing point that a particular focused spectral region, between 6600–7200 Å in the supernova restframe, has especially low dispersion.

Let us use this as a guide for exploring future possibilities. We refer to such a notional supernova cosmology survey as the Sparse Spectroscopic Supernova Survey, or \(S^4\); it is sparse in the sense of focusing on select redshift slices and a single spectrum near maximum light. If the spectral calibration does fulfill its promise, then the distance standardization per SN is 0.101 mag, or 0.073 mag with peculiar velocity contributions removed and an improved reference sample, while noting that the intrinsic dispersion found in the focused spectral region is a remarkable 0.02 mag [1, 2]. These three numbers correspond to 4.7%, 3.4%, or 0.92% fractional distance uncertainty respectively. Table I shows the number of SN (and hence spectra) needed for the statistical uncertainty to match the systematics level assigned in Eq. (3), that is

\[
N_{\text{sys}}(\text{dispersion}; z) = \left( \frac{\text{dispersion}}{\text{systematic}(z)} \right)^2. \tag{4}
\]

Such a powerful survey could conceivably be accomplished with some 1700 SN spectra. (Note that a higher systematics floor implies an even lower \(N_{\text{sys}}\).) From the maximum wavelength corresponding to 7200 Å restframe, the end of the lowest dispersion spectral range, we see that the lowest three redshift slices can all be surveyed using CCDs out to 1 µm\(^1\). The highest redshift slice, at \(z = 1\), requires accurate near infrared (NIR) measurements; this will require space observations. Possibly one could push the highest slice to greater \(z_{\text{max}}\), up to \(z = 1.36\) for measurements out to 1.7 µm, and do correspondingly better on dark energy FOM (for a reoptimized \(z = \{0.05, 0.31, 0.41, 1.36\}\), FOM = 344), but we stay with our fiducial \(z_{\text{max}} = 1\).

Other observations needed for this supernova cosmology program, i.e. before targeting them with spectroscopy, are: finding the SN, establishing them as likely Type Ia, estimating the time of maximum light, and measuring the host galaxy redshift. Time domain imaging surveys such as LSST will find hundreds of thousands of SN and can use its six wavelength band observations to estimate type (see, e.g., [11] and related vegetarian developments) and time of maximum. LSST and other galaxy catalogs can provide estimates of host galaxy redshifts.

Remember, we only need ~ 1700 out of the hundreds of thousands of SN so we are free to discard candidates lacking certainty and precision. The focus would be on the optimized redshift slices, i.e. SN in \(z = \{0.03 - 0.1, 0.23, 0.33\}\), [0.33, 0.43], and [0.95, 1.05], say. In the coming era, accurate spectroscopic redshifts for a few thousand host galaxies will also be easy as a supplement to imaging and catalogs.

The use of specific redshift slices can also reduce systematics by itself – i.e. certain redshifts may be less susceptible to systematics by virtue of the cosmology dependence or wavelength band characteristics, as in the studies of k-corrections [12], and filter zero point calibration errors and population evolution [13]. At the least, the systematics could be less diverse, potentially making control or correction easier.

One of the difficulties with pushing beyond \(z_{\text{max}} \approx 1\) is the challenge of obtaining accurate measurements there from ground based imaging. However, if all we need is typing and estimate of maximum light, this may be possible, especially as time dilation helps with cadenced observations at these redshifts. We leave this for future exploration. At low redshift, LSST is not the most efficient SN search survey, and there will be an important role for \(z < 0.1\) surveys. Since SN at these redshifts are readily identifiable, this could be combined with the spectroscopic survey, in a next generation Nearby Supernova Factory. Thus we envision that a combination of the Nearby Supernova Factory\(^+\), LSST, and possibly the Nancy Grace Roman Space Telescope or James Webb Space Telescope for NIR spectroscopy and possibly \(z > 1\) imaging could have important roles in \(S^4\).

An intriguing, but highly speculative, idea is whether sparseness in spectral wavelength could be added to sparseness in spectral phase and in redshift. Further study on the spectral range necessary for effective Twins Embedding, or some additional spectral technique, would be welcome. Also, we do not currently understand why there is only 0.02 mag internal dispersion in the 6600–7200 Å restframe range, and where the additional external dispersion (e.g. up to 0.073 mag) comes from.

\(^1\) The results of [1, 2] use a restframe range of \(\sim 3300 - 8600\) Å; it is not clear how much of this is crucial (dust constraints in general improve the longer the wavelength baseline) or whether one gains most of the impact already by 7200 Å, say. In addition, germanium CCDs under development may allow good measurement out to 1.4 µm, sufficient to reach 1 µm SN restframe for the lowest three redshift slices [9, 10].
the external dispersion could be corrected, then each SN becomes even more powerful.

$S^4$ demonstrates that a carefully crafted next generation supernova cosmology program could be highly illuminating for dark energy, while being observationally efficient.

**IV. CONCLUSIONS**

Recent developments have opened the possibility that supernovae can be exceptionally well calibrated as distance indicators through measurement of their spectra at a single epoch near maximum light. This could lead to a highly time efficient survey with great dark energy sensitivity: one spectrum per SN, at a single epoch, with excellent statistical dispersion, and strong cosmological leverage from a small number of selected redshift slices.

Planned wide field, deep, time domain surveys such as LSST will provide an extensive candidate list from imaging, then the best few thousand would be selected for spectrophotometric measurements following an optimized, sliced redshift distribution. Carefully crafted sparseness in redshift can be quite powerful and more efficient than a filled redshift range; we saw that it requires an increase of 25% in the SN sample having the traditional even, rather than optimized, distribution to be essentially equivalent to the optimized result for the dark energy figure of merit.

The dark energy figure of merit for this Sparse Spectroscopic Supernova Survey, $S^4$, approaches an impressive 300, assuming stringent systematics control is enabled by the recent advances in spectrophotometry, aided both by the demonstrated low dispersion and by the focused redshifts. We also assessed the impact of varying the low and high redshift ends, and the systematics level. A combination of LSST and Roman or JWST, and a low redshift survey such as a next generation Nearby Supernova Factory, would feed into and complement $S^4$. The outstanding sensitivity of supernovae for dark energy, and their systematics distinct from other probes, motivate a central role for them in next generation cosmology.

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