Type Ia Supernovae & Cosmic Acceleration

Greg Aldering

Lawrence Berkeley National Lab, One Cyclotron Rd., Berkeley, CA, 94720

Abstract. The current application of Type Ia supernovae to the determination of the expansion history of the universe is discussed. Work by two separate research teams — the Supernova Cosmology Project, and the High-Z Team — has shown that the most straightforward interpretation of observations of Type Ia supernova at $\langle z \rangle \sim 0.5$ is that the expansion of the universe is accelerating. The form of this acceleration is consistent with a positive value of Einstein's "cosmological constant." Various forms of systematic error, both intrinsic and extrinsic to Type Ia supernovae have been proposed as alternative explanations. I review the constraints on systematic errors provided by current observations, and then discuss improvements which will be possible with a new sample of nearby supernovae and planned future observations of $z > 1$ supernovae. Assuming that systematic errors are negligible, or can be converted into statistical errors, large homogeneous samples of very distant Type Ia supernovae hold the potential to determine several key cosmological parameters to an accuracy rivaling or exceeding that of planned CMB observations. A satellite concept designed to bring this promise to fruition is outlined.

INTRODUCTION

Type Ia supernovae have proven to be an extremely valuable class of cosmic explosion. The copious luminosity of these events has long held great potential as cosmological distance indicators. It is now known how to standardize the peak brightnesses of these events using information from the timescale of the explosion [1–3]. This knowledge has been exploited by the Supernova Cosmology Project, as well as the High-Z Team (see Kirshner, these proceedings) to measure the expansion history of the universe. Using independent methods of correcting Type Ia supernova peak brightnesses for the width/decline rate of the lightcurve, and using mostly separate sets of supernovae, both groups have come to the conclusion that the expansion of the universe is accelerating.

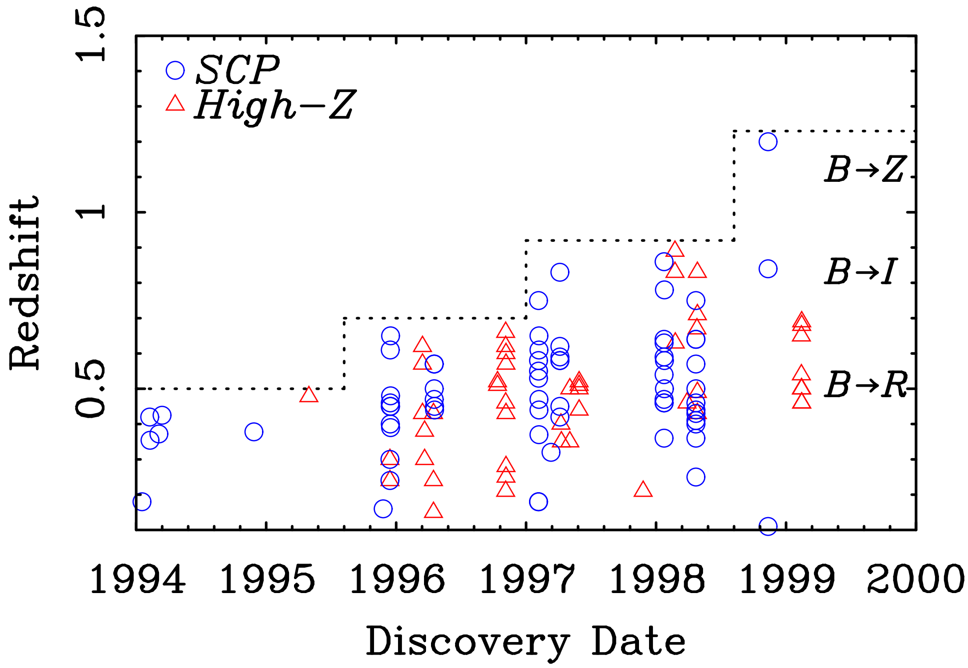

FIGURE 1. Discoveries of spectroscopically confirmed Type Ia supernovae at cosmological distances up through the time of this meeting, compiled from the IAU Circulars. The contributions of each of the research groups, the Supernova Cosmology Project (SCP) and the High-Z Team, are shown separately. The observer-frame filter covering the rest-frame B-band is shown on the right for several redshift ranges. As of this writing the most distant of these is SN1998eq, discovered at Keck II by the SCP [4].

CURRENT RESULTS

Unlike other cosmological distance indicators, SNe are not static, cataloged objects. The effort to discover them requires resources comparable to the cosmologically relavent follow-up observations, and entails significant risk. Ingredients for successful supernova searching include a 3-week gap between reference and discovery images, with full moon between, providing discoveries near maximum light with follow-up in dark time; large CCD mosaics ($\sim$ 1/4 sq deg per field); use of sites and season with clearest weather (Chilean summer); and Keck spectroscopy + CTIO/WIYN/HST follow-up photometry (with VLT/Gemini/Subaru/MMT/Magellan valuable new additions). Special challenges include fast ($<$ 12 hrs) reduction & subtraction of search images, scheduling coordination of different telescopes (esp. *HST*), and attention to bad-weather back-up scenarios. Progress in discovering more spectroscopically confirmed Type Ia supernovae — and at ever increasing distances — is portrayed in Fig. 1.

The confidence regions in the Ω_M,Ω_Λ plane have tightened from the wide band of [5], which was consistent with the then-expected Einstein-de Sitter model, to a proper ellipse with the addition of a Type Ia supernovae (SN1997ap) at $z = 0.83$

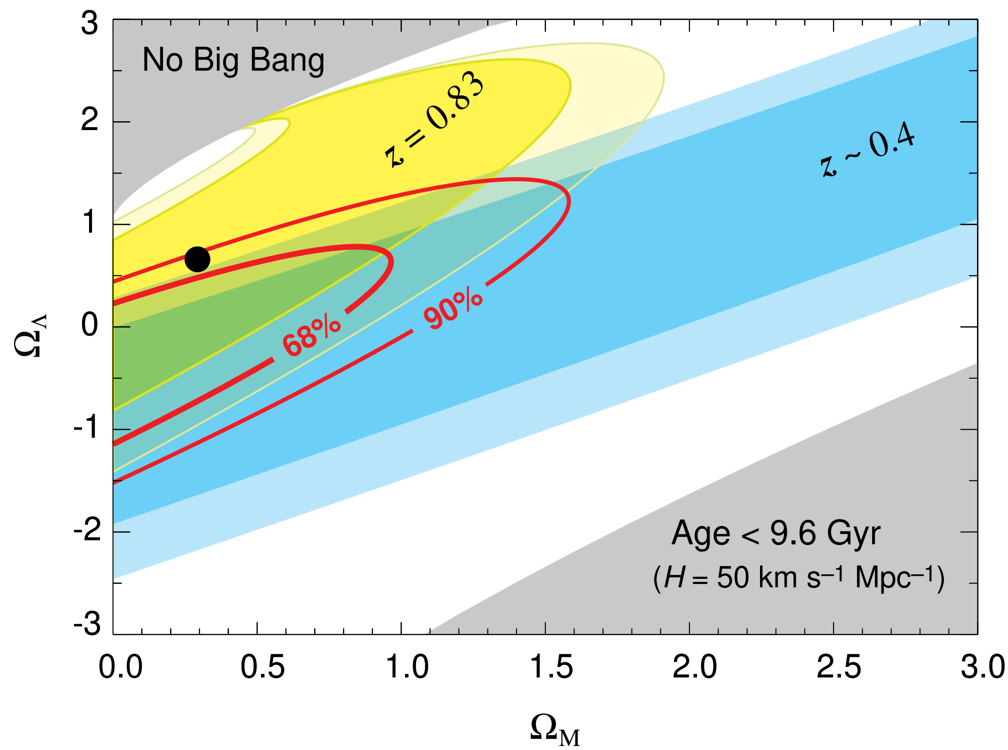

FIGURE 2. The first Type Ia supernova constraints on cosmological parameters. The blue band is from the seven supernovae of [5], the blue region is the constraint from the $z = 0.83$ supernova, SN1997ap, and their combined constraints for 68% and 90% probability are drawn as the red ellipses (from [6]). The black circle indicates the current best-fit values of Ω_M and Ω_Λ for a flat universe from [7]. The presence of a probable, but spectroscopically unconfirmed, Type Ic supernova in the dataset of [5] at that time lead to a weak preference for an Einstein-de Sitter universe. However, those early results are still consistent with the best current results.

and observed with HST [6] — both shown in Fig. 2— and then to the smaller error ellipse rejecting an Einstein-de Sitter model and favoring a (flat) universe with a positive cosmological constant [7,8], shown in Fig. 3. Two independent research groups reached this same result, and the indications of low Ω_M from galaxy cluster dynamics and abundances, combined with indications of a flat universe from CMB measurements, are also consistent with this result. The discovery of such “dark energy” — now playing a dominant role in the expansion of the universe — presents an exciting new puzzle for fundamental physics to explain.

CONSTRAINING SYSTEMATIC UNCERTAINTIES

A more prosaic interpretation of the Type Ia supernova observations is that some systematic error leads to an apparent dimming of supernova at higher redshift,

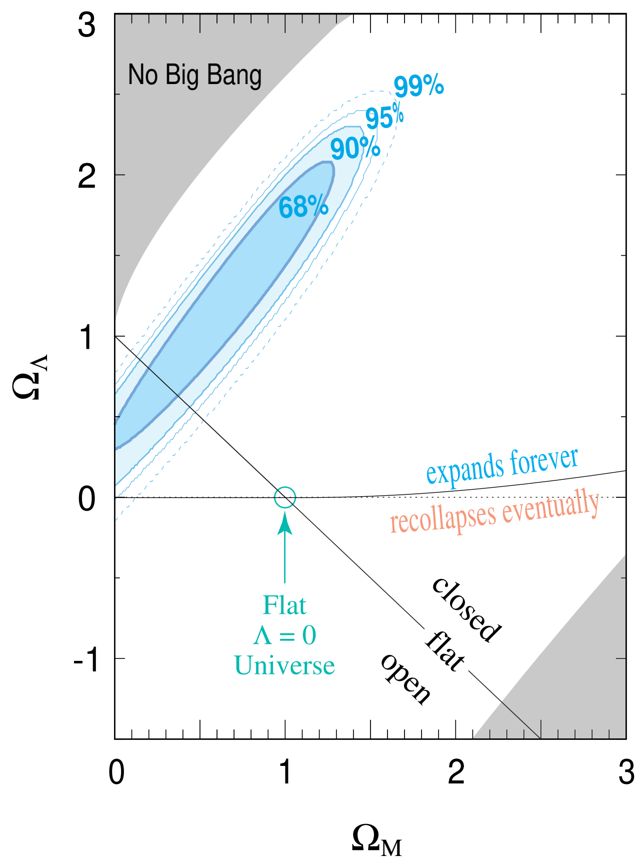

FIGURE 3. The most recent Type Ia supernova constraints on cosmological parameters, from [7]. These results, based on 42 high-redshift and 18 low-redshift suerpnovae rule-out the Einstein-de Sitter model. They also require a cosmological constant if the curvature of the universe is zero. Even after marginalizing the probability over Ω_M, there is still strong evidence for a cosmological constant from these data.

thereby mimicking a cosmological constant. The history of astronomy is filled with examples where dust extinction or evolution of a "standard candle" has lead to misinterpretation of observations, so such concerns cannot be treated lightly. Several classical systematics, such as Malmquist bias, host galaxy extinction, and gravitational lensing are examined in [7] and found to be unlikely as alternative explanations. Another aspect of the high-redshift dataset which many find puzzling is the small amount of host galaxy extinction inferred from the supernovae colors in concert with standard dust extinction laws. [9] have modeled the extinction expected for Type Ia supernovae observed through galaxy halos and randomly oriented disks. I have then taken their simulations and applied the additional bias against heavily extincted supernovae which arises in a flux-limited search. These two cases are shown in Fig. 4; the disk and halo results are shown with their

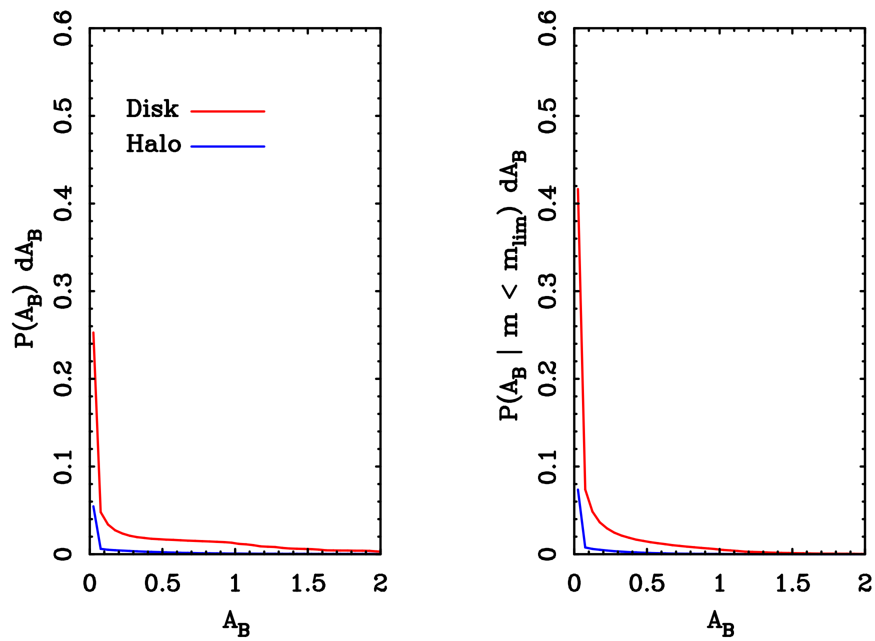

FIGURE 4. The expected extinction probability distribution of Type Ia supernovae, with (right) and without (left) inclusion of bias due to flux-limited selection. The extinction distributions are shown separately for halo and disk populations, according to their relative frequencies in the galaxy population.

correct relative normalization. The surprising result is that almost half of the Type Ia supernovae discovered in the high-redshift searches should suffer less than 0.025 magnitudes of extinction in the rest-frame B-band. This is consistent with the actual observations of [7] and [8]. Extinction of gravitational lenses, as in [10], have very different selection biases and geometries which favor the higher observed extinctions. Similarly, some of the differences in the radial distribution of various low- and high-redshift supernova samples seen by [11] also include a contribution due to the selection against AGN used by the SCP — namely, a small brightness change at the center of a galaxy is generally not followed with spectroscopy at Keck due to the high probability it will be due to variability of an AGN.

Recently, [12,13] have claimed there is a difference in the time from explosion to peak between low-redshift and high-redshift supernovae, and have speculated that such a difference in rise-times might translate into a difference in peak brightnesses. As discussed at length at the conference, a more complete analysis of the data finds that these time scales are in fact reasonably consistent and that features of the current datasets can easily bias attempts to measure a difference [14]. Thus, rise-time differences are no longer a likely alternative to a cosmological constant, although for completeness this question will have to be revisited once more suitable datasets become available.

Dust extinction has always been the astronomer's nemesis, and [15–17] (and these

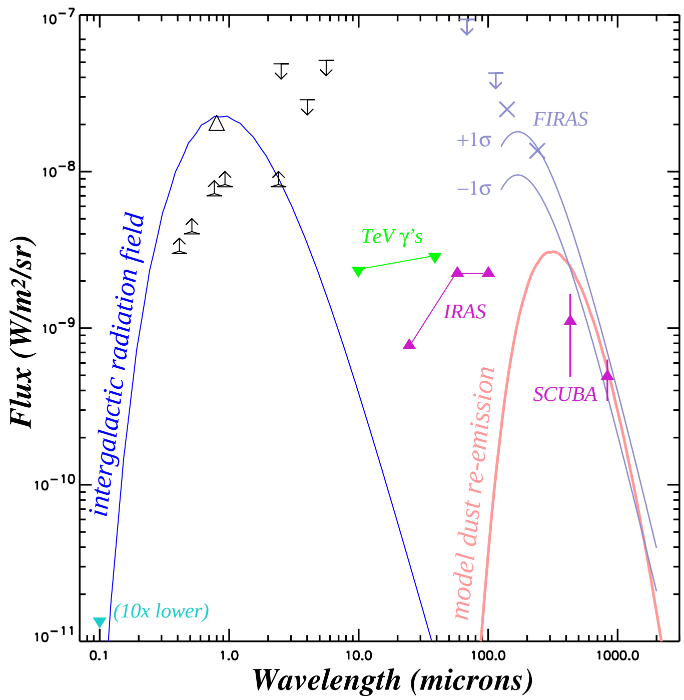

FIGURE 5. Gray dust emission and constraints. The intergalactic radiation field (optical-NIR) from galaxies will heat an gray dust, which will then re-emit in FIR. The dust re-emission shown is that expected if there is enough gray dust to explain the Type Ia supernova observations without a cosmological constant, and is adapted from [17]. I have added lower limits from IRAS and SCUBA galaxy counts from [19], and upper limits in the EUV from [20] (drawn 10× too high so as to fit on graph), and MIR upper limits from TeV γ-ray absorption from [21]. The SCUBA galaxy counts nearly account for the background observed by FIRAS [18], leaving limited room for intergalactic gray dust.

proceedings) has proposed that intergalactic dust with an extinction law which is nearly flat (gray) at optical wavelengths could explain the Type Ia supernovae observations without a cosmological constant. Such dust doesn't strongly redden supernova light, and there are few other observational constraints on whether such dust could exist. Perhaps the most promising direct means of limiting the amount of such dust is through observations of the cosmic far-infrared background (CIB). As Fig. 5 illustrates, the intergalactic radiation field from galaxies will heat the dust to a temperature slightly warmer than the CMB. FIRAS has measured such an excess, but galaxy counts at 850μm seem able to account for most of this background at wavelengths relavent for re-radiation by intergalactic dust [18,19]. Future deep sub-mm observations resolving the CIB should settle this questions. In the meantime, we can state that a preliminary analysis of SN1999eq at $z = 1.20$ indicates that it has a peak brightness expected from extrapolation of the best-fit cosmological

TABLE 1. Nearby Supernova Campaign: Survey Parameters

Search	Type	Aper (m)	FOV (deg^{-2})	Scale ("/pixel)	Exp (sec)	Filter
EROS	Staring	1.0	1.00	0.60	300	B & R
MOSAIC	Staring	0.9	1.00	0.43	240	R
NEAT	Staring	1.0	2.54	1.40	60	open
Spacewatch	Scanning	0.9	$0.57\times t$	1.05	430	OG515
QUEST	Scanning	1.0	$2.30\times t$	1.00	550	V

parameters of [7]. If gray dust were present in quantities sufficient to explain the observations of [7,8], SN1999eq should have been dimmer.

THE SPRING 1999 NEARBY CAMPAIGN

Another potential systematic error would occur if Type Ia supernova explosions are different at low- and high-redshift. Such an error — sometimes referred to as evolution — could arise it the current peak luminosity - lightcurve width relation does not already correct for variations in Type Ia supernova initial conditions and if the mean value of some initial parameter changes systematically with redshift. Such changes in initial conditions must be well synchronized with redshift or else the luminosity dispersion for high- and low-redshift supernovae would be different, contrary to what is observed [7].

Type Ia supernovae in nearby galaxies can help settle the question of whether the luminosity-width relation works over a wide range of initial conditions. Supernova spectroscopic features, as well as stellar population indicators from the host galaxies, can serve as initial condition indicators. Since the nearby universe contains stellar populations that are both young and old, metal-poor and metal-rich, it should be possible to find local counterparts to high-redshift supernovae. With this in mind, the SCP coordinated an extensive campaign to find a large number of nearby Type Ia supernovae and obtain extensive follow-up observations of them during the spring of 1999. In this endeavor, the SCP was joined by members of the EROS and QUEST collaborations, the Nearby Galaxies Supernova Search Team [22], and received early alerts of supernova candidates from LOSS [23], the MSSSO Abell Cluster Search [24], the Wise Observatory supernova search [25], and the Tenegra Observatory search [26]. The NEAT [27] and Spacewatch [28]asteroid search teams also contributed data which was used for searching.

Table 1 gives the parameters of the searches, broken down by facility, and then totaled at the bottom. In all cases CCD detectors were used, and in most cases the same SCP search software used for high-redshift searching was also used for the Nearby Campaign. This largely eliminates several systematic bias which plagued large photographic supernova searches [30,29]. Over 1300 sq. deg. of sky was

TABLE 2. Nearby Supernova Campaign: Survey Results

Search	Time (hrs)	Coverage (deg^2)	Ia	II	Ic	Untyped (faint)
EROS	125	∼450	11	3	0	10
MOSAIC	48	∼175	6	2	0	1
NEAT	15	∼425	3	1	1	0
Spacewatch	140	∼150	3	0	0	2
QUEST	4	∼140	0	0	0	1
Other Searches[a]			6	2	0	0
Totals		∼1340	29	8	1	14

[a] LOSS, MSSSO Abell Cluster Search, Wise Obs., etc, discussed elsewhere in these proceedings

searched in this campaign. Table 2 presents a summary of the supernovae discovered by the Nearby Campaign, and Fig. 6 shows the redshift distribution of the discoveries. Of the Type Ia supernova, 20 were discovered early enough and at low enough redshift to warrant intensive follow-up observations. The redshift distribution of these "select" supernovae is also given in Fig. 6. Follow-up observations consisted of $UBVRI$ photometry every 3–7 days, and spectrophotometry once per week. In all, some 100 nights of telescope time were used to search, and another 100 nights were used for follow-up. The amount of spectroscopic coverage equals that of all Type Ia supernova spectra published to date, and the temporal coverage is far better than the average (e.g., a discovery spectrum near peak). Analysis of this dataset is underway, and we expect it to yield much firmer constraints on how well the luminosity-width relation accounts for different initial conditions amongst Type Ia supernovae.

ON-GOING AND FUTURE ADVANCES

While concerns regarding systematic uncertainties are being addressed, the SCP is also pushing forward with new observations of high-redshift supernovae to better constrain Ω_M, Ω_Λ, and the curvature, Ω_k. Observations of over a dozen more Type Ia supernovae having exquisite observations from HST PC2 and NICMOS are being analyzed, including SN1999eq at $z = 1.20$ which was one of the last science targets observed by NICMOS before its cryogen ran out.

Even with Keck and HST, progress in increasing the high-redshift Type Ia supernovae samples is slow going (see Fig. 1). A sample of 2000 Type Ia supernovae out to redshift $z \sim 1.7$ would enable measurements of Ω_M to ± 0.02, Ω_Λ to ± 0.05, and Ω_k to 0.05 from supernova alone. Adding the constraint of a flat universe (Ω_k $= 0$) would enable such a dataset to measure Ω_M and Ω_Λ to ± 0.01. Moreover, since Type Ia supernovae can map the expansion history of the universe explicitly,

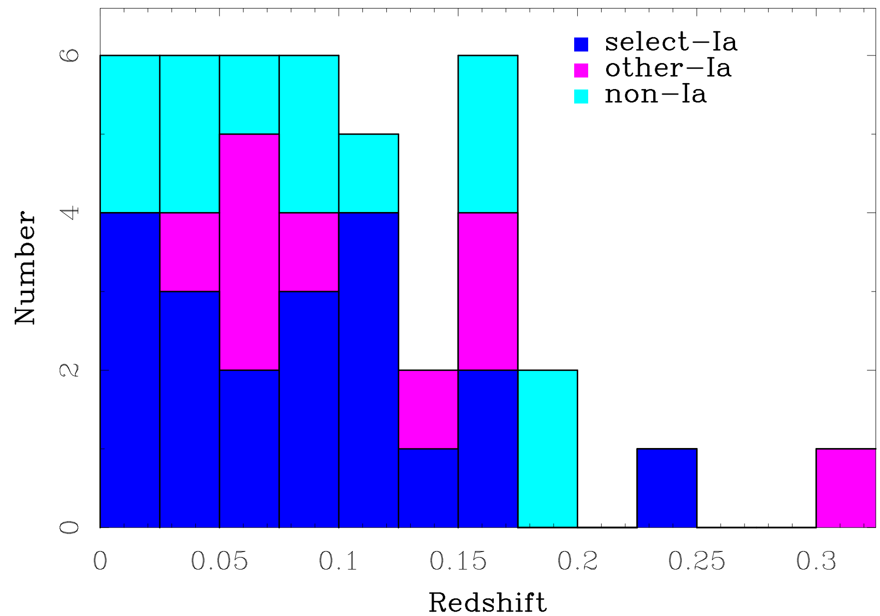

FIGURE 6. Redshift distribution of the Spring 1999 Nearby Campaign.

such a dataset would allow a determination of whether the "dark energy" is really a cosmological constant of whether an different (perhaps time varying) equation of state applies.

Given this potential for making Type Ia supernovae a pillar of observational cosmology — and an important complement and check for measurements of the CMB — and our assessment that obtaining such a large dataset with excellent control over systematics from the ground is difficult at best, the SCP has developed a concept for a dedicated wide-field imager and optical/NIR spectrograph in space. In one year such a satellite could discover and obtain photometric and spectroscopic follow-up for 2000 Type Ia supernovae out to $z \sim 1.7$. The supernovae would be discovered very early, eliminating Malmquist bias and allowing measurement of their rise-times. Optical through NIR spectroscopy at peak would allow checks on several important indicators of explosion luminosity, kinetic energy, metallicity, etc., while also allowing correction for host galaxy extinction for a variety of extinction laws. Although NGST has plans to observe Type Ia supernovae as well, constraining the nature of the "dark energy" requires observations at $z < 1$, where searching with NGST would be prohibitive and the budget for follow-up observations would be dominated by the slew time rather than time on target. With dedicate space-based facility, the number of well observed high-redshift a decade from now could be 100× larger than it is today.

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