TYPE IA SUPERNOVAE & THE ACCELERATING UNIVERSE

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Work by two independent research teams — the Supernova Cosmology Project and the High-Z Team — has shown evidence using Type Ia supernovae at $\langle z \rangle \sim 0.5$ that the expansion of the universe is accelerating. Observations of the CMB and cluster abundances confirm these findings, while new tests have strengthen the case for Type Ia supernovae as reliable distance indicators. In addition to reviewing these findings, this talk will discuss programs which are now being developed to obtain much tighter cosmological constraints using Type Ia supernovae, and which should also lead to a much better understanding of their behavior.

1 Introduction

The expansion history of the Universe is of fundamental scientific interest. In the context of General Relativity, this expansion history allows the universal mass density, Ω_M, and curvature, Ω_k, to be determined. Whether mass is the only dominant constituent of the Universe can be determined by comparing $\Omega_k$and Ω_M. Any other constituent, Ω_X, which does not behave like mass can be determined by the relation $\Omega_k = 1 - \Omega_M - \Omega_X$ (for the observationally established case that the radiation density is now much less than the mass density). Einstein considered Ω_X in the form of a cosmological constant, Ω_Λ, as a remedy for an otherwise unappealing Universe which would not sit still. Hubble's subsequent discovery that the Universe is expanding dispelled the notion of a static Universe with a careful balance between Ω_M and Ω_Λ, causing further consideration of Ω_Λ to fall into disfavor. However, in spite of our human sense of aesthetics, Nature seems eager to utilize any available degree of freedom.

Since Ω_M and Ω_Λ (or Ω_X) enter into the expansion rate with different powers of $(1+z)$, measuring the expansion history of the Universe to sufficiently high redshift allows these two parameters to be measured independently[10]. (Presently the data (see below) do not allow this, but it is an ultimate goal.) Application of classical astronomical measures of expansion history thus require objects whose properties can be measured to high redshifts. The most promising tool for such studies is the peak brightness of Type Ia supernovae. At peak, such supernovae are as bright as the entire Milky Way galaxy, and their cosmological potential has long been recognized[6].

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2 Early Progress

The first half of the last decade witnessed two nearly simultaneous breakthroughs in exploiting Type Ia supernovae as cosmological probes. First, the substantial sample of Type Ia supernovae in the Hubble flow discovered by the Calan-Tololo survey[11] lead to the recognition and calibration of a relation between the lightcurve timescale and peak brightness[28,29]. Application of this correction reduced the intrinsic dispersion in the peak brightness of "normal" Type Ia supernovae from $\sim 35\%$ to $\sim 17\%$, and even to $\sim 10\%$ after correction for extinction by dust in the supernova host galaxy. Thus, the relative distances to Type Ia supernovae can be determined with an accuracy of 5%.

The second breakthrough was the discovery of cosmologically useful Type Ia supernovae. The Supernova Cosmology Project (SCP) discovered and obtained a lightcurve for SN 1992bi[24], followed by several more Type Ia supernovae with both lightcurves and spectral confirmation in 1994 (SN 1994G, etc.). The High-Z Team found and obtained follow-up for its first distant Type Ia supernova, SN 1995K, about a year thereafter[34]. These discoveries were made possible with the advent of the searching power of new wide-field CCD mosaics, and the spectroscopic power of the Low-Resolution Imaging Spectrograph[22] on the Keck telescopes.

2.1 Search Technique

The search portion of supernova cosmology requires resources comparable to follow-up, and entails significant risk. Thus, it is worth recounting the search technique which as been developed to a level at which successful supernova searches are the norm. First of all, timing is an essential ingredient for successful supernova searching. By obtaining reference and comparison images with a 3-week gap (comparable to the supernova risetime), with full moon between, the discovered supernovae will be near maximum light, and the initial follow-up observations can be obtained in dark time. Without such careful scheduling, half of the supernova discovered will be after maximum light, and precious follow-up time would be wasted establishing that fact. The second critical component is the search facility, which must consist of a large CCD imager (covering at least 1/4 deg^2) on a 4-m or larger telescope located at a site where the skys are reliably clear (such as Chile in the summer). Without reliably clear weather coupled with large areal coverage, discovery of a sufficient number of supernovae to justify follow-up telescope time can not be guaranteed. The final key component is properly scheduled access to the most powerful facilities for spectroscopic type and redshift determination (e.g. at Keck & VLT) and photometric follow-up (e.g. with HST). The sequence of observations is illustrated in Fig 1 using our actual data obtained during a search campaign in March 1998. Supernovae which are discovered but cannot be followed provide no more cosmological information than if the search run had failed. Supernova searching is quite an exciting undertaking, but it is quote sobering to think of the large amount of precious telescope time riding on the outcome!

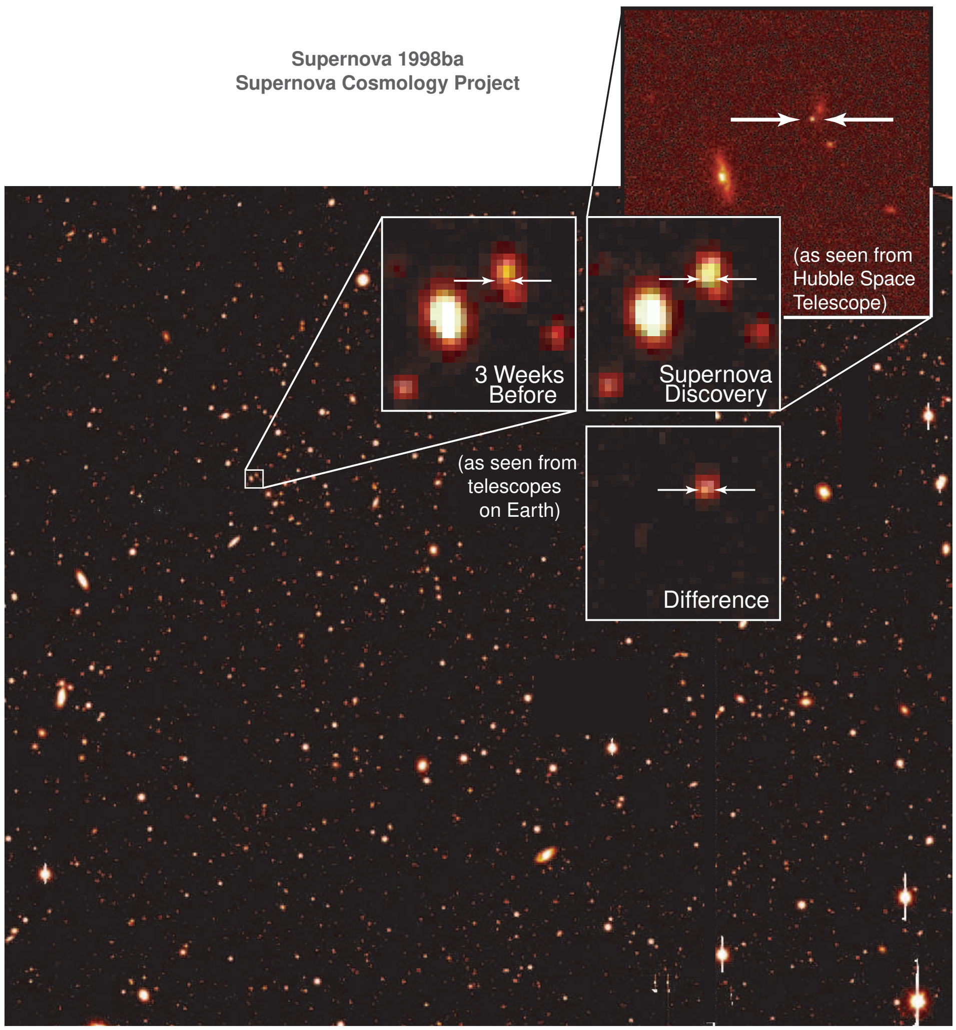

Figure 1. Illustration of the basic search and follow-up datasets needed for cosmology with high-redshift supernovae. Wide-field CCD images contain thousands of anonymous galaxies. Images taken at two epochs roughly 3 weeks apart are convolved to the same image quality and digitally subtracted. Excess light with a point-like appearance is a candidate supernovae. Follow-up observations, such as the HST image shown here, provide confirmation of the supernova and are used to obtain its lightcurve

2.2 First Cosmological Constraints from Type Ia Supernovae

Perlmutter *et al.*[25] presented the first constraints on Ω_M and Ω_Λ using Type Ia supernovae. The seven supernovae in this sample were consistent with an Einstein-de Sitter universe (no curvature and no cosmological constant). This initial sample of $z \sim 0.4$ supernovae was augmented with a single additional Type Ia supernova

(SN 1997ap) at $z = 0.83$ — the first supernova with a lightcurve from HST — in Perlmutter *et al.*[26]. By itself this supernova slightly disfavored an Einstein-de Sitter universe, but it was still consistent with the initial Perlmutter *et al.*[25] results.

3 Current Results

The current constraints on Ω_M and Ω_Λ imposed by the SCP high-redshift supernova data[27] in concert with the low-redshift data of Hamuy[11] are shown in Fig 2. The first surprise from this result was the strong rejection of an Einstein-de Sitter universe. The second, even greater, surprise was that the marginalized probability distribution function for Ω_Λ allows less that a 1% probability that Ω_Λ is not greater than zero[27,30]. This is the basic evidence from Type Ia supernovae that there is a finite cosmological constant (or other form of dark energy, Ω_X) accelerating the expansion of the universe.

The need for dark energy to explain the supernova results is reinforced when results from *either* the CMB or Ω_M-sensitive studies from structure growth are added. The structure growth data require Ω_M in the neighborhood of 0.3[7]. For $\Omega_M \sim 0.3$ in Fig. 2, the supernova data require $\Omega_\Lambda \sim 0.7$ — and strongly reject a non-zero value of Ω_Λ. Likewise, the CMB data which now strongly favor a flat universe[17], also overlaps with the supernovae data around $\Omega_\Lambda \sim 0.7$. The values $\Omega_M \sim 0.3$ and $\Omega_M \sim 0.7$ are thus consistent with the key observational data[8], and are surprising close to the "concordance" values suggested back in 1995[23]. Fig 3 illustrates this concordance using the best data available at the time of this conference.

3.1 Internal Checks

Naturally this evidence for dark energy was a great surprise to the SCP when it was first seen in our data. Accordingly, a inordinate amount of care has gone into the analysis of the data[27]. Our large sample allowed us to examine the data for outliers. This showed that one of the supernovae in the initial SCP dataset[25] was an outlier; this supernova was examined further and shown to be a probable Type Ic. This was one of the few supernovae in the SCP dataset for which a spectrum of the supernova could not be obtained to establish the type. The earliest SCP results were pulled in the direction of an Einstein-de Sitter model by this single supernova, demonstrating that spectral confirmation of type for supernovae to be used for cosmology is essential. This lead us to reexamine all the spectra of supernovae in the current sample, and Perlmutter *et al.*[27] present results for subsamples selected by our confidence in the supernova type, which show that further selection based on type quality has no effect on the results.

We also examined the distribution of stretches for our high-redshift supernovae and compared it with the stretch distribution of the low-redshift comparison sample. This comparison showed excellent agreement, with a mean stretch of 1.00 ± 0.01 for the high-redshift supernovae and 0.99 ± 0.01 for the low-redshift supernovae. Although the standard stretch-luminosity correction would correct for differences in stretch between low- and high-redshift supernova, it is comforting to see that we are finding supernovae of similar stretches at all redshifts.

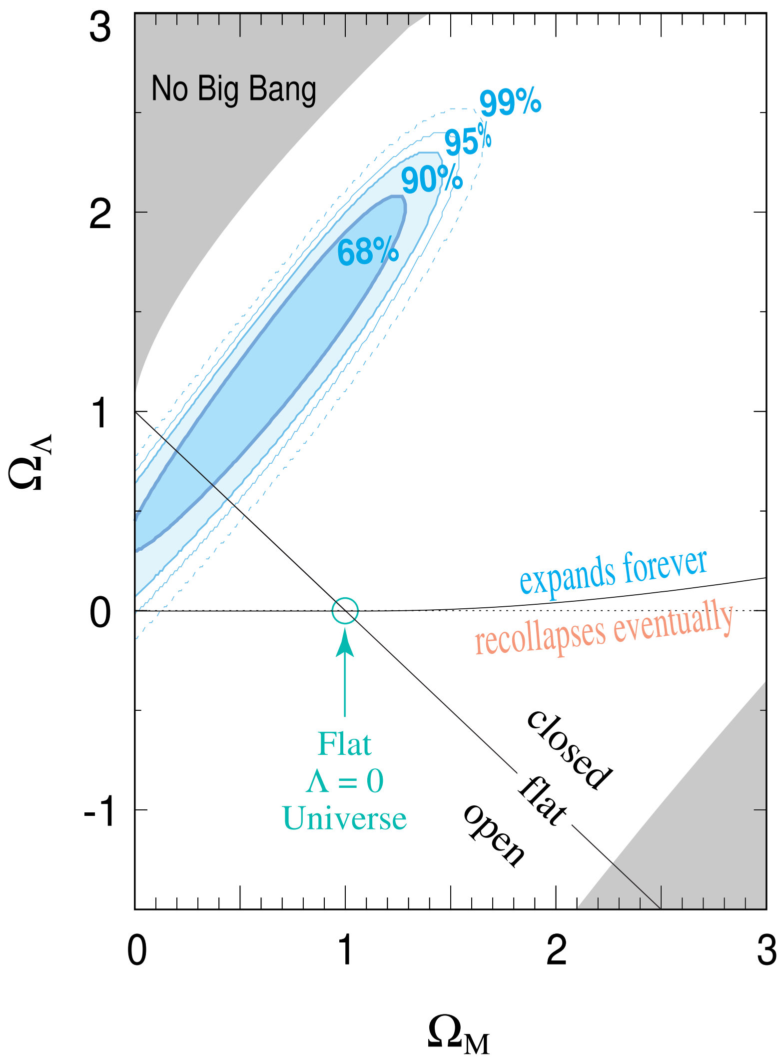

Figure 2. Constraints in the Ω_M— Ω_Λ plane from the 42 high-redshift supernovae of Perlmutter *et al.* 1999

We also examined the distribution of supernova colors, which are indicative of the amount of extinction the supernovae suffer due to "ordinary" dust in their host galaxies. If the mean amount of extinction were constant with redshift it would not be necessary to even correct for it. We find first that the amount of extinction is low for most of our supernovae, as well as for supernovae at low-redshift. This is consistent with models of the dust distribution within galaxies[13],

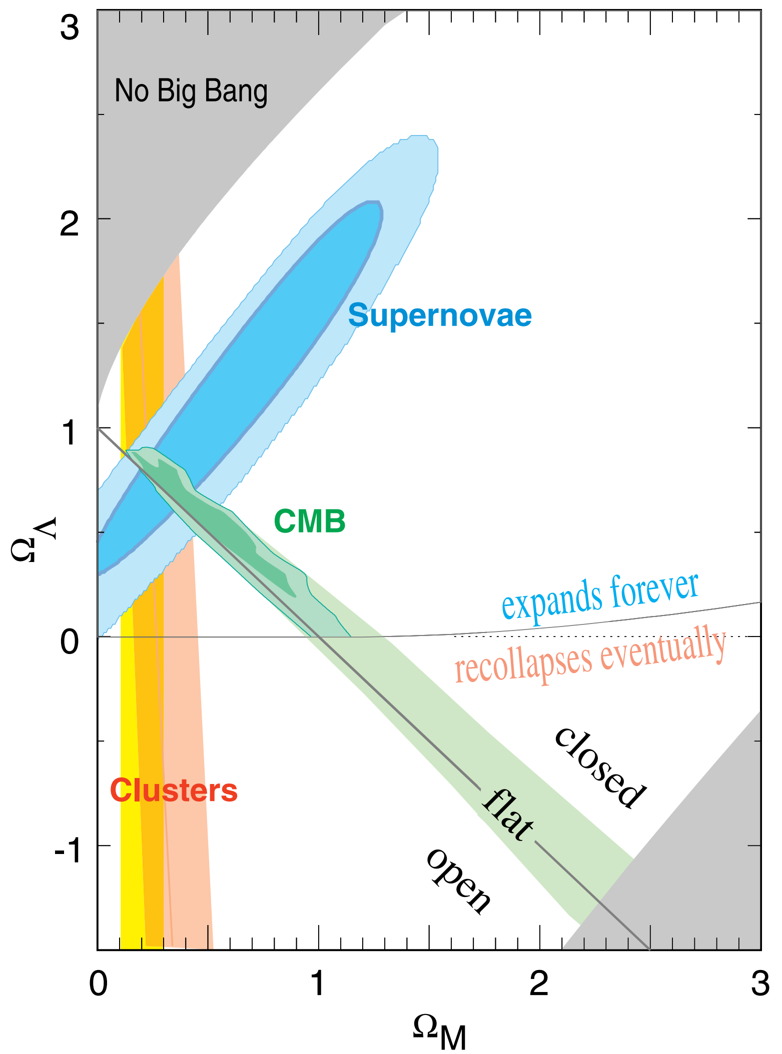

Figure 3. Confidence regions in the Ω_M—Ω_Λ plane from our Type Ia supernovae, from cluster abundances from Bahcall & Fan 1998, and from combining the latest CMB observations by BOOMERANG-98, MAXIMA-1, and COBE/DMR (Jaffe *et al.* 2000).

especially when combined with the selection which operates against discovery of extincted supernovae[4]. We also find (within the considerable uncertainties) that the low- and high-redshift supernovae have similar color distributions. Unfortunately not all of our supernovae have measured colors, and so there remains the small possibility that those without colors suffer more extinction than the rest of the sample. Our analysis was performed both with and without correction for host galaxy extinction, with little difference in the results. We also found that use of

Bayes Theorem to eliminate the extinction correction for supernovae which are "too blue" can lead to biases in the cosmological analysis because the true extinction distribution is poorly known; we therefore recommend against its use.

Additional checks included a conservative approach to account for gravitational lensing; if all the mass is clumped into compact objects it would result in the demagnification of most supernovae, making them appear dimmer in the same sense as a cosmological constant. We found that even under the conservative assumption that all supernovae are demagnified by the maximum amount, an Einstein-de Sitter is still strongly ruled out and the need for dark energy remains as strong. The basic reason that the evidence for dark energy is not weakened by inclusion of gravitational lensing demagnification is that most of the probability at small Ω_Λ is also at small Ω_M (see Fig 2), where there is no mass to magnify or demagnify background objects. Thus, the probability distribution for $\Omega_\Lambda$is not altered near the critical $\Omega_\Lambda = 0$ value, and the probability of $\Omega_\Lambda > 0$ is preserved.

4 Potential problems?

Although the supernova results appear secure based on the internal checks, we must continue to examine all credible alternatives to a cosmological dark energy. The difficulty dark energy presents for current fundamental physics is one reason for doing so, but another reason is to understand what effects may ultimately limit the use of Type Ia supernovae as cosmological probes. The two concerns which cannot be resolved with the supernova datasets of Perlmutter *et al.*[27] and Riess *et al.*[30] are whether abnormal dust extinction is making the supernovae too faint[2] or whether the high-redshift supernovae are intrinsically dimmer at high-redshift (commonly referred to as "evolution"). We examine each of these in the light of new observational constraints.

4.1 Intergalactic gray dust extinction?

Aguirre[2,1] has suggested that intergalactic space is filled with dust grains which have been expelled from galaxies. Moreover, he considers these grains to be sufficiently large that their Mie scattering cross-section is fairly wavelength independent over the optical wavelengths were the high-redshift supernovae have been observed. Since this dust would not alter ("redden") the observed colors of the supernova — as would dust like that in our Galaxy — it would be undetectable with the current observational dataset. There is a credible case[1] that the necessary amount of heavy elements needed to form an intergalactic reservoir of large silicate and graphite grains has been synthesized in stars over the age of the universe, and even that these heavy elements are in fact missing from galaxies and so must be in the intergalactic medium.

Such dust grains will absorb light from the intergalactic radiation field — comprised of the light of multitudes of galaxies and quasars — and reradiate this energy at far infrared wavelengths. Indeed a far infrared background has been measured from the COBE/DIRBE experiment[14], and this background constrains the properties of such dust grains. If the far infrared background is not ultimately completely resolved into discrete galaxies and quasars[4], then there would be strong evidence in support of the existence of intergalactic gray dust.

Supernovae data over a longer wavelength baseline can also be used to set limits on the amount of intergalactic gray dust since this dust does slightly alter the colors of supernovae. Current limits based on restframe B- and I-band color observations of one high-redshift supernova disfavor gray dust at about the 2σ level as the sole explanation for the dimming of high-redshift supernovae[33].

Additional limits on the amount of intergalactic gray dust come from our observations of a Type Ia supernova (SN 1998eq) at $z = 1.2$[5]. If gray dust were responsible for 30% dimming of supernovae at $z \sim 0.5$, then the amount of dimming out to $z = 1.2$ would be much greater still. However, our preliminary peak brightness for this supernova is completely consistent with an Ω_M=0.3, Ω_Λ=0.7 universe with no gray dust. Observations of additional very high-redshift supernovae will be needed to completely reject the gray dust model by this approach. It must be borne in mind that some small amount of intergalactic dust probably is present and eventually will have to be accounted for as cosmological measurements based on luminosity distance become more precise.

4.2 Differences between Low- and High-redshift supernovae?

The simple one-parameter relation between lightcurve timescale (stretch) and peak luminosity corrects for 90% of the luminosity variance amongst different Type Ia supernovae. This relation corrects supernova residing in old, metal-rich elliptical galaxies as well as those residing in younger spiral galaxies, many of which are metal poor. Thus, it is likely that we have already witnessed most of the range of initial conditions a Type Ia supernova can experience, and that most of the differences in explosion initial conditions are already accounted for. This makes it unlikely that supernovae at $z \sim 0.5$ cannot be standardized using the local stretch-luminosity relation.

Indeed, we see the same range in stretch for the low-reshift and high-redshift samples (see above), and the ages and metallicities of the stellar populations at low- and high-redshift have considerable overlap. Thus, it would appear that the only place left for significant redshift-dependent differences to hide would be in the 10% luminosity variance that is still unexplained. Imagine there exists a second parameter that explains the residual 10% luminosity variance; if one accepts that at least some of the low-redshift calibrating supernovae have a second parameter value that overlaps with those at high-redshift, then this second parameter could affect the SCP cosmology results by at most 0.1 magnitudes if all the high-redshift supernovae were at the 1σ extreme of the second-parameter distribution function. Since the SCP supernovae are 0.3 magnitudes fainter than they would be in Ω_M= 0.3 universe without a cosmological constant, this extreme second-parameter example does not provide a credible alternative to a cosmological constant.

Since the metals in galaxies build-up over time from nucleosynthesis within stars, there is an expectation that supernovae at higher redshifts might come from lower-metallicity environments. Fortunately recent work has shown that the canonical B-band photometry of Type Ia supernova is hardly affected by changes in the metallicity of unburned layers of the supernova ejecta, while the ultraviolet spectrum is affected[19] in a way that that allows straight-forward measurement of the metallicity. Moreover, there are plenty of examples of metal-poor galaxies at low-redshift as well new examples of metal-rich galaxies at high-redshift[18]. Thus, the expected correlation of metallicity with redshift is weak and cannot be used in posit the existance of differences between low- and high-redshift supernovae.

Recently there has been some concern that the risetimes of low redshift supernovae are longer than those of the supernovae in the SCP dataset[31]. The risetime is defined as the time from explosion to maximum light, corrected to $stretch = 1$, and was found to be ~ 20 days by Riess *et al.*[32]. According to Höflich *et al.*[15], a change in risetime of 1 day could lead to a change in the peak supernova brightness by $\sim 10\%$. Riess *et al.* compared their low-redshift risetime to a preliminary estimate based on a stretch-corrected composite lightcurve constructed by combining all the lightcurve points from the $z \sim 0.5$ supernovae in the SCP supernova sample[27]. My collaborators and I[3] have since performed a very thorough analysis of the SCP supernova sample and found a risetime of 18.2 ± 1.2 days (statistical), consistent with the low-redshift risetime. We also showed that for the SCP dataset, systematic errors of several days in the measured risetime can result from variations in the post-maximum exponential lightcurve tail (a case of the tail wagging the dog!). Therefore, the current high-redshift supernova datasets are not accurate enough to constrain evolution with redshift in the risetime of Type Ia supernovae.

5 What's next?

5.1 Recent progress

Since our initial results we have discovered and obtained good-quality follow-up spectroscopy and photometry for another ~ 18 Type Ia supernovae in the redshift range $0.4 < z < 1.2$. Of these, 12 have lightcurves obtain with WFPC and NICMOS on HST, giving these 12 supernovae the statistical weight of roughly 26 of our older high-redshift supernovae. In addition, inclusion of supernovae at higher redshift will dramatically shorten the major axis of our error ellipse. The progress expected in better constraining Ω_M,Ω_Λ over the next few years is illustrated in Fig 4.

We have also gotten into the business of discovering and following low-redshift supernovae. This became necessary in order to improve the calibration of the stretch-luminosity relation, to better understand the selection effects (e.g., leading to Malmquist bias), and to search for any additional parameters controlling the supernova peak brightnesses. In spring of 1999 the SCP, in cooperation with several other supernova search groups and near-earth asteroid search groups, discovered over 40 nearby supernovae in a single two month period. Of these, 19 were Type Ia supernovae discovered near peak and these were chosen for extensive photometric and spectroscopic follow-up. Indeed, the spectral coverage achieved with this low-redshift supernova campaign is unprecedented and should offer a wealth of new information on the physical processing governing the explosion. More information on this new low-redshift dataset can be found in Aldering 2000[4,21].

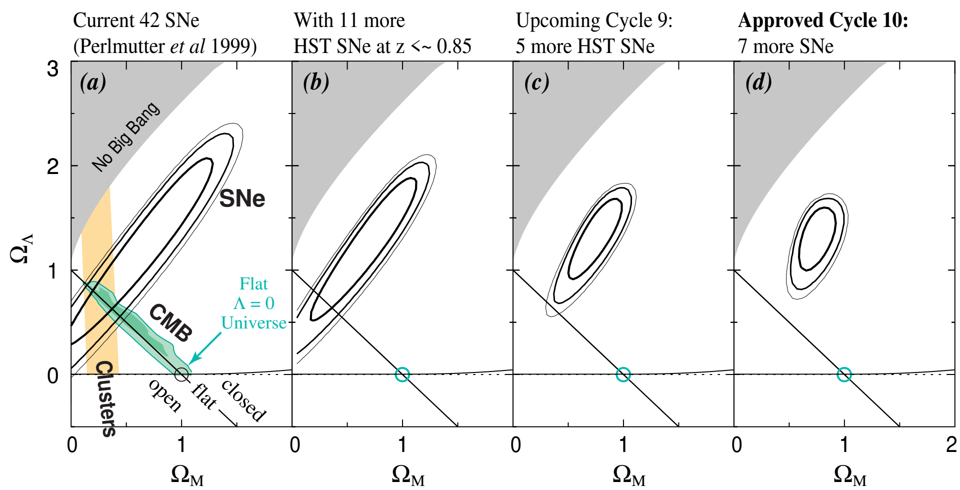

Figure 4. Illustration of how we expect the supernova constraints to tighten over the next few years as more supernova (especially at higher redshifts and observed with HST) are measured. For simplicity, we have let the confidence regions collapse around our current best fit, which — although consistent with a flat universe — is not centered on the flat universe locus.

5.2 The Nearby Supernova Factory

To achieve the ultimate accuracy in measuring the cosmological parameters, Type Ia supernovae will have to be understood much better than they are today. Accordingly, we have launched a new collaboration, the Nearby Supernova Factory (*SNfactory*), which will capitalize on the success of our spring 1999 low-redshift campaign. By partnering with the Near-Earth-Asteroid-Tracking (*NEAT*) team at JPL to search their survey data in near-realtime, the *SNfactory* expects to discover several supernova every clear night. This is an order of magnitude increase over current supernova searches. Rather than running for only 2 months — as we did in spring 1999 — the *SNfactory* will be run year-round. A dedicated integral field spectrograph and imager (*SNIFS*) is being built by our collaborators in France for follow-up spectrophotometry of *SNfactory* supernova discoveries. By obtaining a spectral image (x, y, λ), either spectra or synthesized broadband images can be constructed (mimicking the standard B-band photometry most commonly used for supernova lightcurves). We plan to have *SNIFS* regularly available at the bent-Cassegrain focus of the University of Hawaii 2.2-m telescope of Mauna Kea (arguably the best astronomical site in the world). Operation of the *SNfactory* is expected to commence in mid-2002. The extensive knowledge gained from the *SNfactory* will the lay the necessary foundation for future supernova cosmological measurements.

5.3 SNAP

Obtaining tighter constraints on the cosmological parameters will require more than an order of magnitude increase in the number of usable high-redshift supernovae, coupled with a 5× decrease in the systematic uncertainties. Lowering the systematics will require improvements in observing technique to minimize, e.g., Malmquist bias and measure risetimes. The likely need to correct for additional physical parameters beyond the current lightcurve stretch parameter will require a substantial reduction in the observation uncertainty per supernova to keep the observational uncertainty close to the current intrinsic peak-brightness uncertainty of 10%.

In considering how to achieve such a goal, our firsthand experience with the limitations of the current ground-based program, in comparison with the great strides made possible with space-based observations from HST, was very influential. Indeed, once one accepts the necessity to control systematic uncertainties at better than the 2% level, one is forced to conclude that only minimal improvements can be made from the ground and that a space-based mission is essential for Type Ia supernovae to reach their full potential as cosmological probes. For instance, due to the increasing brightness of the ground-based night sky at the redder wavelengths to which cosmologically useful Type Ia supernovae are redshifted, the deepest imaginable ground-based supernova searches cannot provide useful data much beyond $z \sim 0.7$ due to the Malmquist-like biases introduced by incompleteness and the inability to obtain color measurements needed to correct each supernova for extinction by dust in its host galaxy. (Note that current ground-discovered supernovae at $z > 0.7$ *are* biased at the level of several percent, and their colors have been measured from space.) These limitations are illustrated in Fig 5, where the sky noise, smoothed to correspond to a redshifted B-band filter and redshifted V-band filter, is compared to the supernova signal required to obtain early discover or a color at peak.

Our concept for the next generation of cosmological exploration with Type Ia supernovae is a 2-m space-telescope dubbed the Supernova/Acceleration Probe (*SNAP*). A three mirror anastigmat design provides a wide field, with small central obscuration and an accessible focal plane having diffraction-limited image quality at 1 μm. Since ultraviolet wavelength coverage is not required, high-efficiency silver coatings can be used, giving an overall telescope throughput of > 95% for optical and near-infrared wavelengths. The primary instrument is the GigaCam imager, which will have a field 650× larger than the camera on HST, with similar resolution. It will be equipped with CCD's developed at LBL[16], which have nearly perfect quantum efficiency out to 1 μm and are radiation hard. The role of GigaCam is to discover supernovae out to $z \sim 1.7$ within a few days of explosion to provide a complete sample and determine the risetime (see above). It will also be used to obtain the follow-up lightcurve photometry, going over peak and out to the exponential tail (whose amplitude is correlated with the C/O ratio in the progenitor star). GigaCam's large field allows it to observe many supernovae simultaneously, thus giving it great power not only for discovery, but for the more demanding follow-up photometry.

GigaCam will be accompanied by two other, more modest, instruments — a

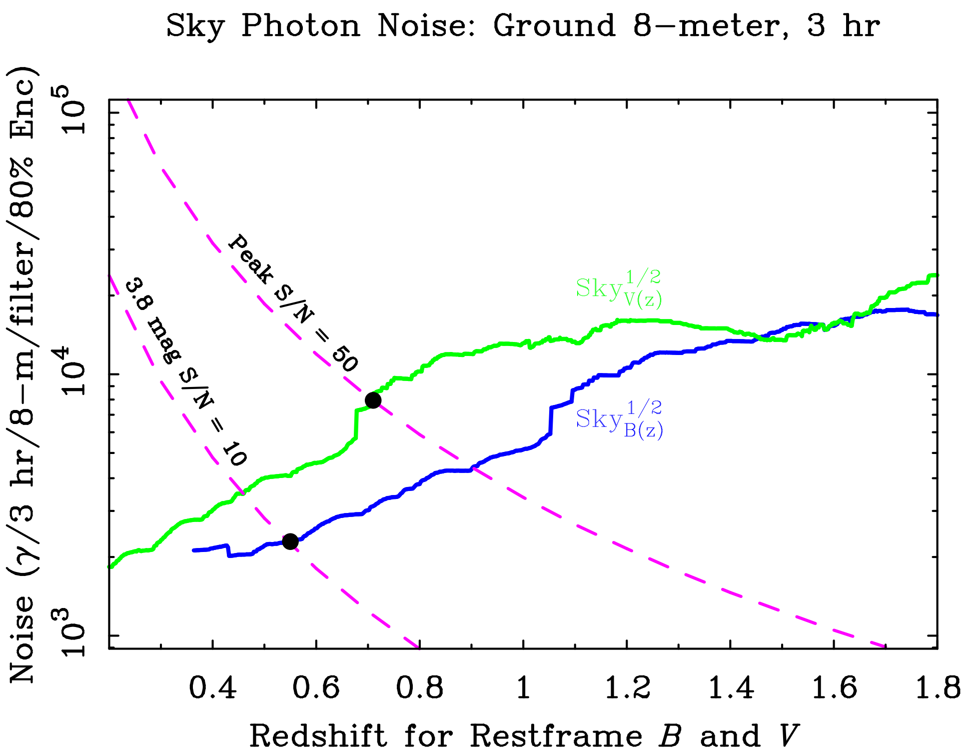

Figure 5. Demonstration of the limitations of ground-based discovery and follow-up of high-redshift Type Ia supernovae. The solid curves are the sky noise obtained in a B-band or V-band filter shifted to a given redshift (given by the abscissa) for a 3 hour exposure with an 8-m telescope on a dark night. The dashed curves represent, respectively, the redshift-dependent loci for the early detection (with signal-to-noise of 10) of a supernova and for measuring its peak color with 2% accuracy. Both measurements are needed — to avoid selection biases (early detection) and to correct for dust extinction (peak color).

near-infrared small-field imager dubbed NIRcam, and a multi-armed spectrograph. NIRcam's role is to obtain the lightcurve photometry for supernovae at $z > 1.2$, whose rest-frame B-band light is redshifted beyond the 1 μm cut-off of GigaCam. Only a sub-sample of these highest-redshift supernovae is required to constrain the amount of intergalactic dust and establish that the matter-dominated era has been reached. Thus, the multiplex advantage of a large field is not as crucial and the small field of NIRcam is perfectly adequate. The spectrograph plays two essential roles. First, it establishes that a supernova is Type Ia by the presence of the strong SiII feature at restframe 0.61 μm; this feature is redshifted to 1.7 μm for the highest redshift *SNAP* supernovae. Second, the spectrograph provides a photometric spectrum of each supernova. This will be used to correct for extinction by dust (including nearly-gray dust) in the host galaxy. It will also be used to measure numerous spectral feature needed to control systematics due to changes with red-

Table 1. SNAP Instrumentation Suite

Instrument	Detectors	Field Size	Wavelength Coverage
GigaCam	LBNL CCD	1 degree^2	0.35 – 1.0 μm
NIRcam	HgCdTe	$1'\times 1'$	1.0 – 1.7 μm
Spectrograph	LBNL CCD+HgCdTe	$2''\times 2''$	0.35 – 1.7 μm

shift in the supernova population (aka "evolution"). The spectrograph is especially powerful because it has an image slicer which greatly simplifies target acquisition and provides the spectrum of both the supernova and its surrounding host galaxy. Moreover, the spectrograph is able to obtain the full supernova spectrum without multiple grating settings by splitting the light into three color ranges which are then sent to spectrograph arms with optics and detectors optimized for each color range. The basic instrument parameters are listed in Table 1.

SNAP will be placed in a lunar-assisted high-earth orbit in order to create a stable thermal environment in which the instruments can be passively cooled to their optimum operating temperatures (150° K for the CCD's, and 80°–140° K for the HgCdTe's). This avoids the need for life-limiting cryogens (as suffered by NICMOS on HST). This orbit can be oriented with apogee over the northern hemisphere, resulting in high visibility from the 11-m radio antenna located at the Space Sciences Lab in the Berkeley hills. A bandwidth of 50 Mbs can be achieved quite readily. *SNAP* will target fields having little dust extinction from our Galaxy, and located towards the north and south ecliptic poles where the background from the zodiacal light is lowest. By concentrating on the ecliptic poles, *SNAP* can operate in a mode where an array of fixed solar panels always face the Sun while the opposite side has a passive radiator emitting into the cold of deep space.

The baseline *SNAP* mission consists of discovery and photometric and spectral follow-up of 2000 Type Ia supernovae in the range $0.1 < z < 1.7$. The statistical goal is to achieve roughly 10% uncertainty per supernova due to measurement uncertainty after correction for lightcurve stretch and host-galaxy dust extinction. This is designed to match the 10% intrinsic dispersion seen for nearby Type Ia supernova, thereby giving the maximum statistical weight per supernova for a give amount of observing time. A simulated Hubble diagram from such a dataset is shown in Fig 6. An equally important — but more difficult — goal is to keep systematic uncertainties due to Malmquist bias, non-Type Ia contamination, non-standard dust extinction, and gravitational lensing below less than 2% between any two $\Delta z = 0.1$ redshift bins (with the lowest and highest bins imposing the most stringent requirements).

The timescale for *SNAP* is ultimately dependend on the availability of funds, but right now a launch in 2007 has been set as a goal. The mission lifetime would be a minimum of three years. Once the supernova mission is accomplished, *SNAP* could be used for other scientifically power surveys, including the discovery of interesting imaging and spectroscopic targets for *NGST*.

The constraints on Ω_M and Ω_Λ from this baseline dataset are overlaid onto our current constraints in Fig. 7. The quality of the *SNAP* dataset will also allow

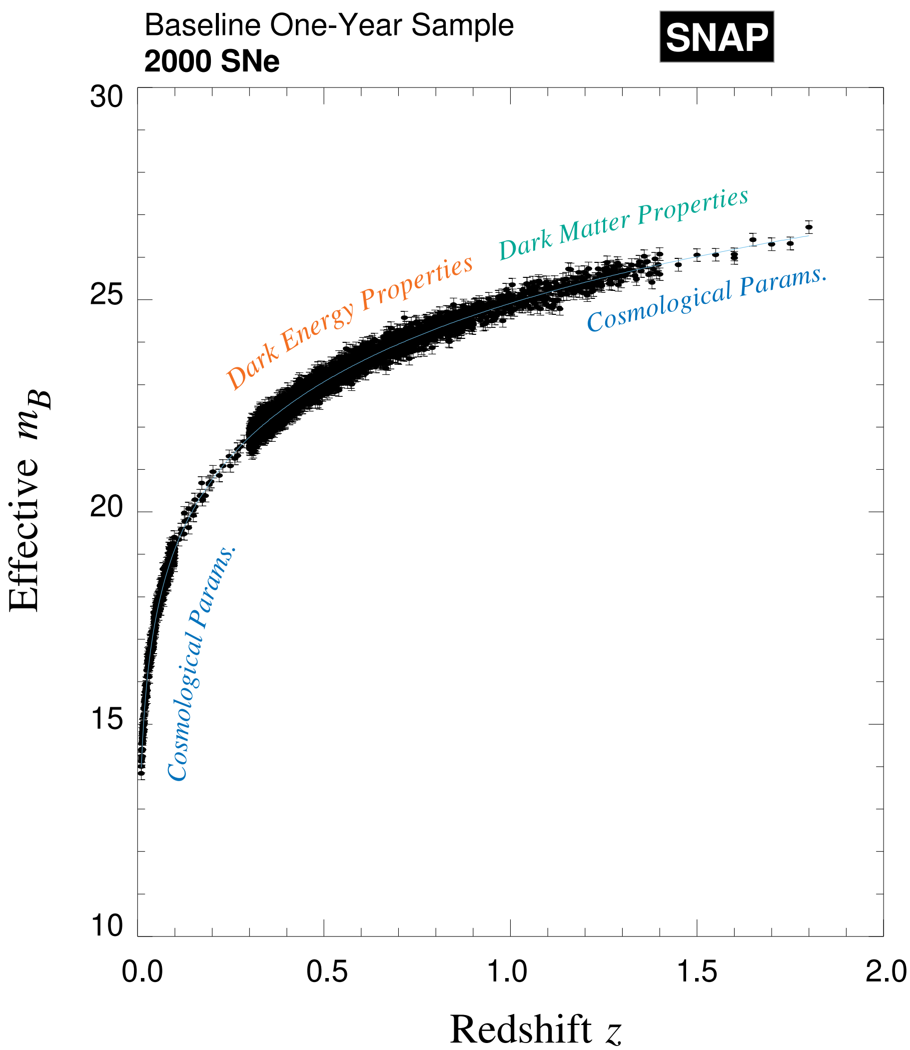

Figure 6. Simulated magnitude vs. redshift (Hubble) diagram for 2000 Type Ia supernovae observed with *SNAP*. The cosmological measurement role of each redshift range is indicated. Each supernova has been assigned an uncertainty of 0.15 magnitudes (15% in brightness), arising in equal parts from measurement errors and intrinsic dispersion. Bear in mind that where there are more supernovae, the Gaussian tails of the error distribution are more noticeable to the eye.

examination of the nature of dark energy by placing strong constraints on the equation of state, w. These constraints are shown in Fig. 8, and should allow *SNAP* to determine whether the dark energy really is Einstein's cosmological constant or something more exotic (e.g., quintessence).

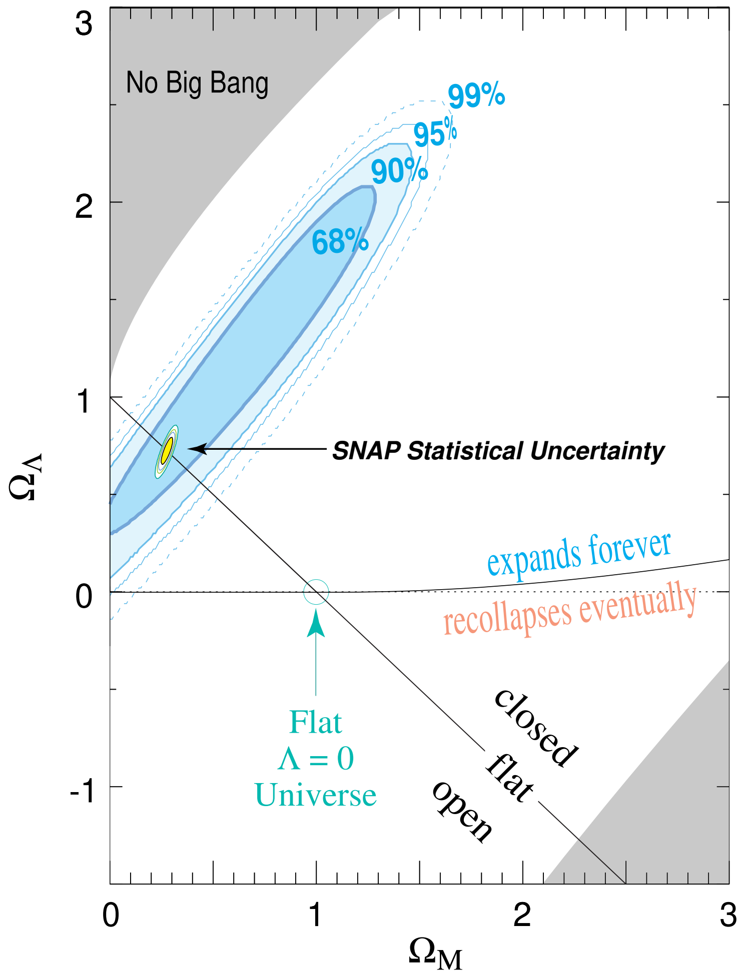

Figure 7. Expected constraints on Ω_M and Ω_Λ from 2000 Type Ia supernovae measured with *SNAP*, overlaid on our current constraints.

6 Summary

Our study of the stretch-corrected peak brightnesses of Type Ia supernovae at high-redshift has provided strong evidence for some form of dark energy which is accelerating the expansion of the universe. This result has been reexamined and critiqued for over two years without any compelling alternative explanation. Indeed, subsequent supernova studies using supernova colors[33], comparisons of the risetimes of low- and high-redshift supernovae[3], or the location of our very high-redshift supernova on the Hubble diagram[5], seem to reinforce the initial results. Moreover, complimentary cosmological constraints from structure formation and the CMB are in full agreement with the supernova results. Indeed, in combination

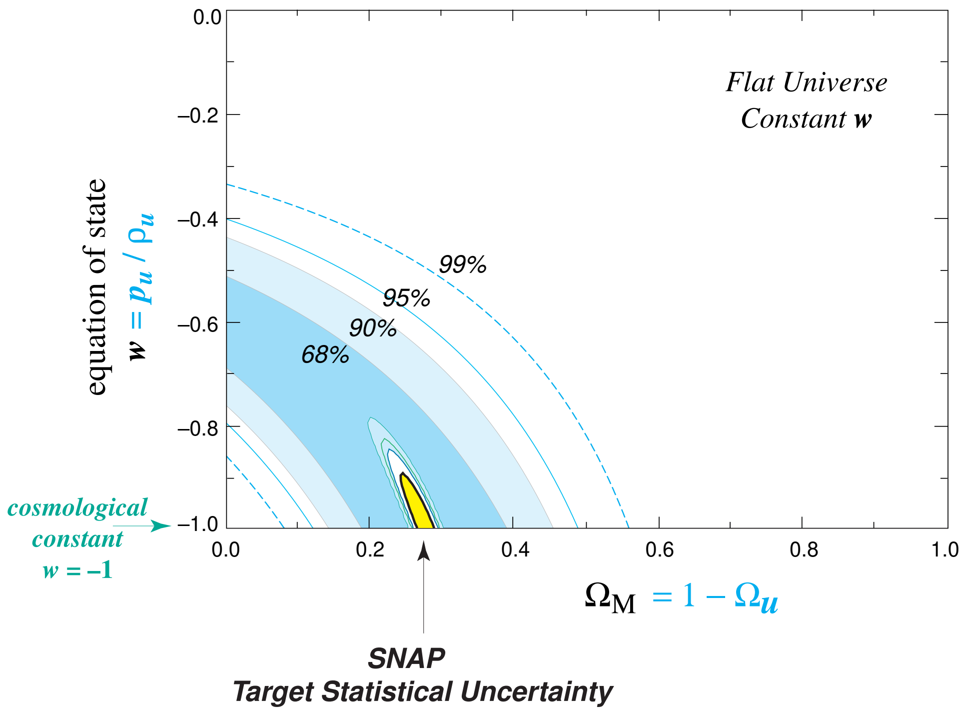

Figure 8. Expected constraints on the equation of state, $w = p_X/\rho_X$, of the dark energy achievable by *SNAP*, overlaid on our current constraints. This example assumes a constant equation of state. For quintessence "tracker" models this is only an approximation to the mean equation of state for $z < 2$. A flat universe is assumed.

these measurements are really pushing for a flat universe with $\Omega_\Lambda \sim 0.7$.

The honing of these cosmological constraints is being vigorously pursued. We hope eventually to not only establish the amount of dark energy, but learn more of its properties such as its equation of state, w. Indeed, since supernovae can probe the range of redshifts where the dark energy dominates, they offer an excellent means of studying not only the dark matter equation of state, but also its first derivative, w'. (This later measurement will require precise knowledge of, e.g., Ω_M[35]). *SNAP* offers the best path to obtaining the maximum amount of cosmological information from the Hubble diagram of Type Ia supernovae. The *SNAP* mission has been carefully constructed to ensure that cosmological parameters — not systematic effects — are being measured. Understanding the underlying supernova physics will be critical for *SNAP* to convincingly achieve its goals. The *SNfactory* will teach us the details of those physical processes, how they can affect the supernova peak brightness, and hopefully how variance due to additional parameters can be used to correct, and thus improve, Type Ia supernovae as cosmological probes.

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