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Cosmology from Type Ia Supernovae

S. Perlmutter, G. Aldering, S. Deustua, S. Fabbro[1], G. Goldhaber, D. E. Groom, A. G. Kim[2], M. Y. Kim, R.A. Knop, P. Nugent, C. R. Pennypacker
Lawrence Berkeley National Laboratory and Center for Particle Astrophysics, U.C. Berkeley

A. Goobar
University of Stockholm

R. Pain
[1]LPNHE, CNRS-IN2P3 & University of Paris VI & VII

I. M. Hook, C. Lidman
European Southern Observatory

R. S. Ellis, M. Irwin, R. G. McMahon
Institute of Astronomy, Cambridge

P. Ruiz-Lapuente
Department of Astronomy, University of Barcelona

N. Walton
Isaac Newton Group, La Palma

B. Schaefer
Yale University

B. J. Boyle
Anglo-Australian Observatory

A. V. Filippenko, T. Matheson
Department of Astronomy, U.C. Berkeley

A. S. Fruchter, N. Panagia
Space Telescope Science Institute

H. J. M. Newberg
Fermi National Laboratory

W. J. Couch
University of New South Wales

(The Supernova Cosmology Project)

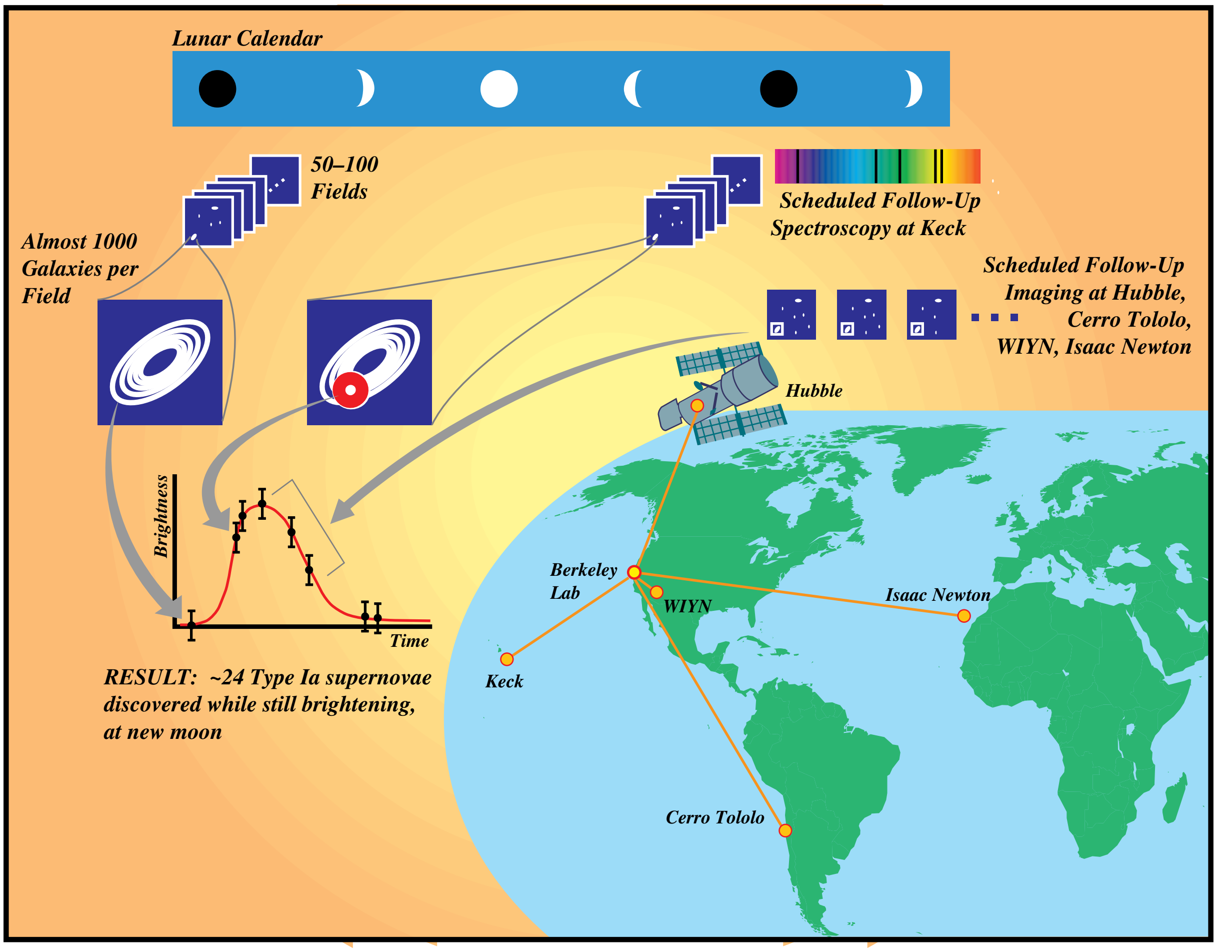
ABSTRACT

This Lawrence Berkeley National Laboratory reprint is a reduction of a poster presentation from the Cosmology Display Session #85 on 9 January 1998 at the American Astronomical Society meeting in Washington D.C. It is also available on the World Wide Web at http://www-supernova.LBL.gov/ *This work has also been referenced in the literature by the pre-meeting abstract citation: Perlmutter et al., B.A.A.S., volume 29, page 1351 (1997).*

This presentation reports on first evidence for a low-mass-density/positive-cosmological-constant universe that will expand forever, based on observations of a set of 40 high-redshift supernovae. The experimental strategy, data sets, and analysis techniques are described. More extensive analyses of these results with some additional methods and data are presented in the more recent LBNL report #41801 (Perlmutter et al., 1998; Ap.J., in press), astro-ph/9812133.

Cosmology from

Strategy

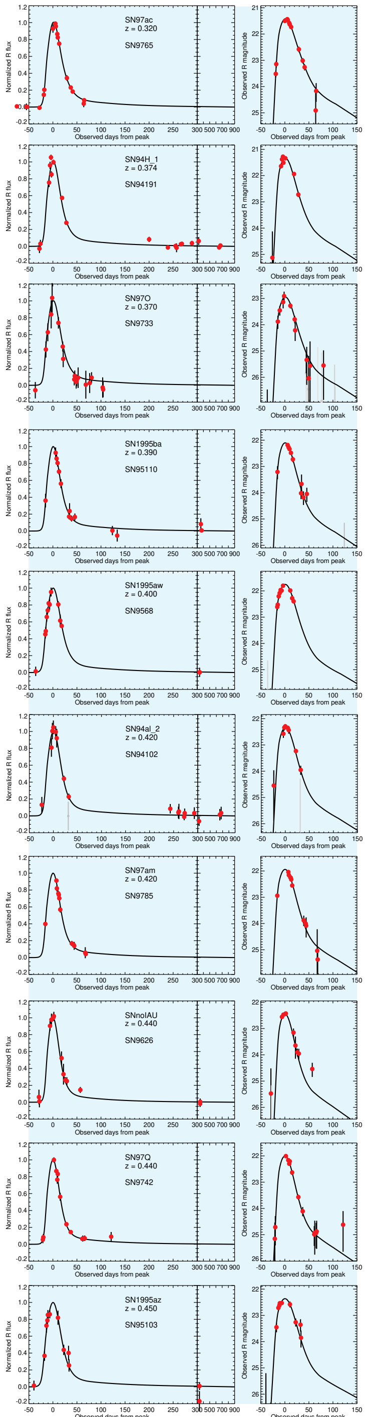


Perlmutter, *et al.*, in **Thermonuclear** *Supernovae*, NATO ASI, v. 486 (1997)

We developed a strategy to guarantee a group of supernova discoveries on a certain date. Just after a new moon, we observe some 50 to 100 high-galactic lattitute fields—each containing almost a thousand high-redshift galaxies—in two nights on the Cerro Tololo 4-meter telescope with Tyson & Bernstein's wide-field camera. We return three weeks later to observe the same fields, and then examine the images of all of the tens of thousands of galaxies. On average, some two dozen Type Ia supernovae will thus be discovered just before new moon—and while still brightening, since the three week time baseline is less than the rise time of a Type Ia supernova. We follow the supernovae, with spectroscopy at maximum light at the Keck telescope, and with photometry over the following two months at the CTIO, WIYN, INT, and (particularly for the highest redshifts) the Hubble Space Telescope.

Type Ia Supernovae

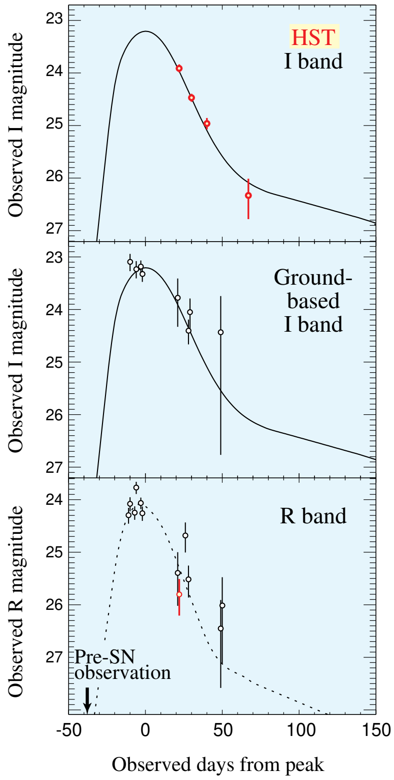
from $z = 0.32$ ...
observed from the ground



Light Curves

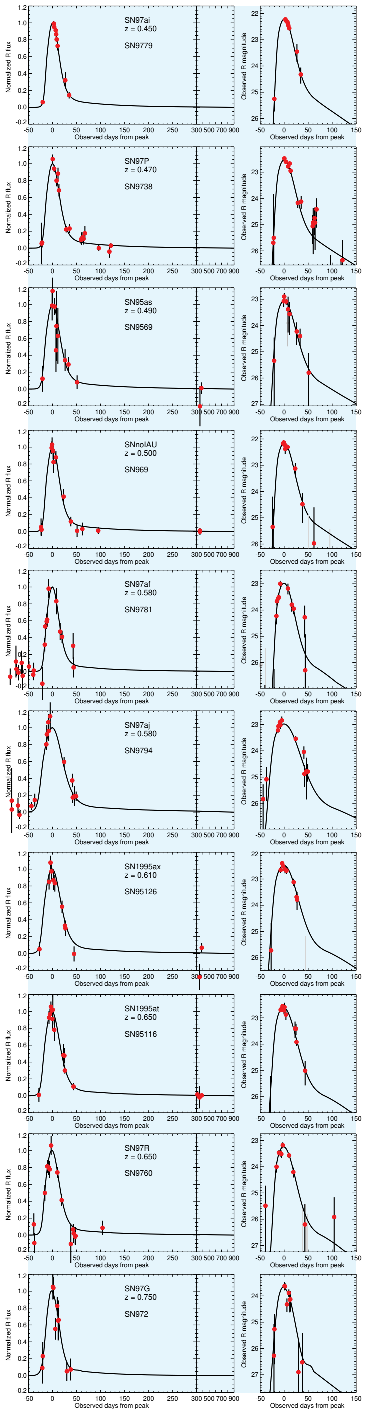
SN 1997ap at $z = 0.83$
observed from the ground and with the HST

Perlmutter, *et al.*, Nature (1998)



We observe most of the supernovae for approximately two months in both the R and I bands (corresponding approximately to the restframe B and V bands for the median redshift). At high redshifts, a significant fraction of this host galaxy light is within the seeing disk of the supernova, so final observations about one year later are usually necessary to observe (and subtract) the host galaxy light after the supernova has faded. The plots to the left and the right show just the R band light curves for about half of the 40 supernovae that have been completely observed and analyzed so far. The plots above show the highest redshift spectroscopically confirmed supernova, which was observed with the Hubble Space Telescope.

... to $z = 0.75$
observed from the ground

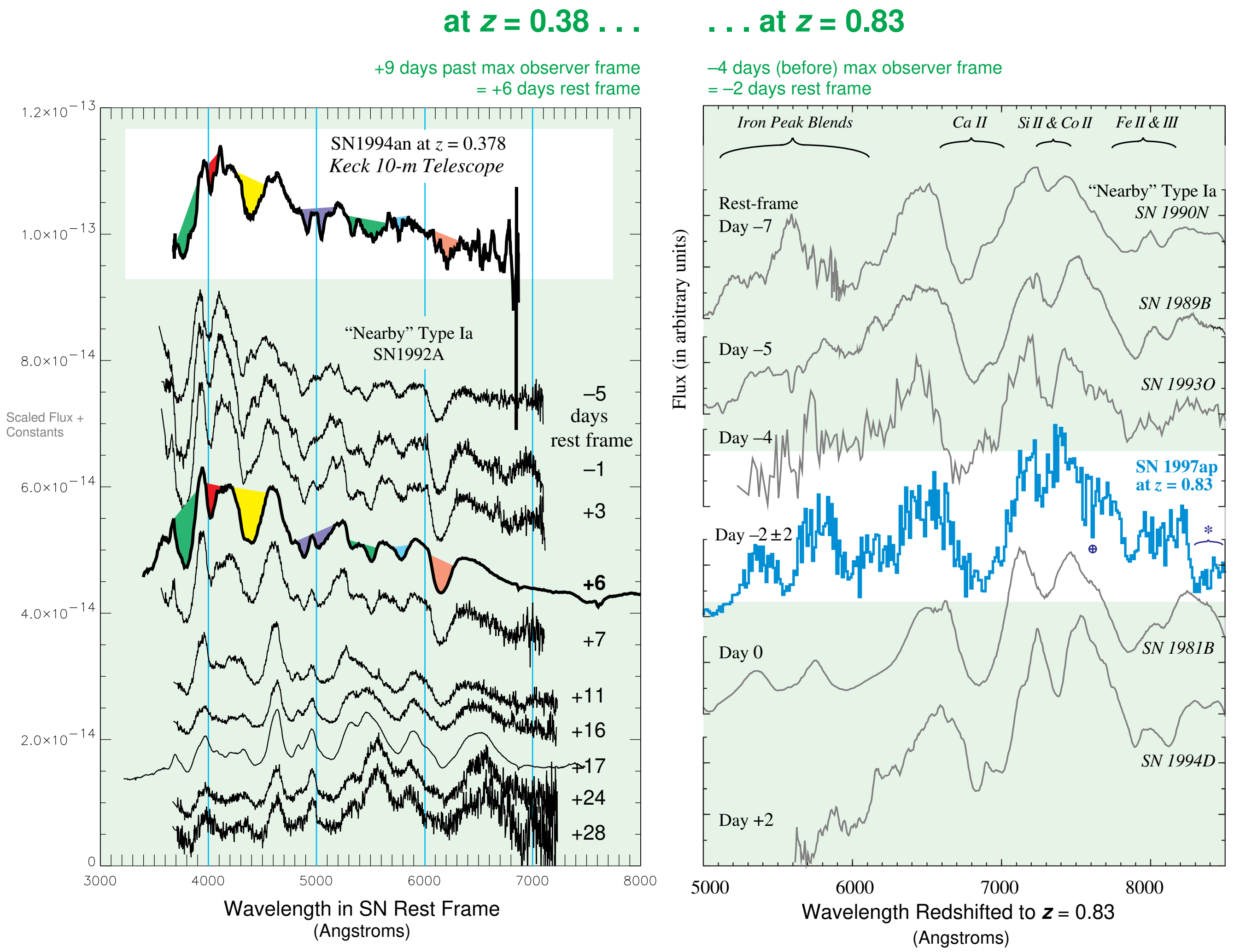


SUPERNOVA COSMOLOGY PROJECT

S. Perlmutter, G. Aldering, S. Deustua, S. Fabbro, G. Goldhaber, D. Groom, A Kim, M. Kim, R. Knop, P. Nugent,
Lawrence Berkeley National Laboratory & Center for Particle Astrophysics, U.C. Berkeley

N. Walton *Isaac Newton Group*; A. Fruchter, N. Panagia *Space Telescope Sci. Inst.*; A. Goobar *Univ. of Stockholm*; R. Pain *IN2P3, Paris*; I. Hook, C. Lidman *European Southern Obs.*

Spectra

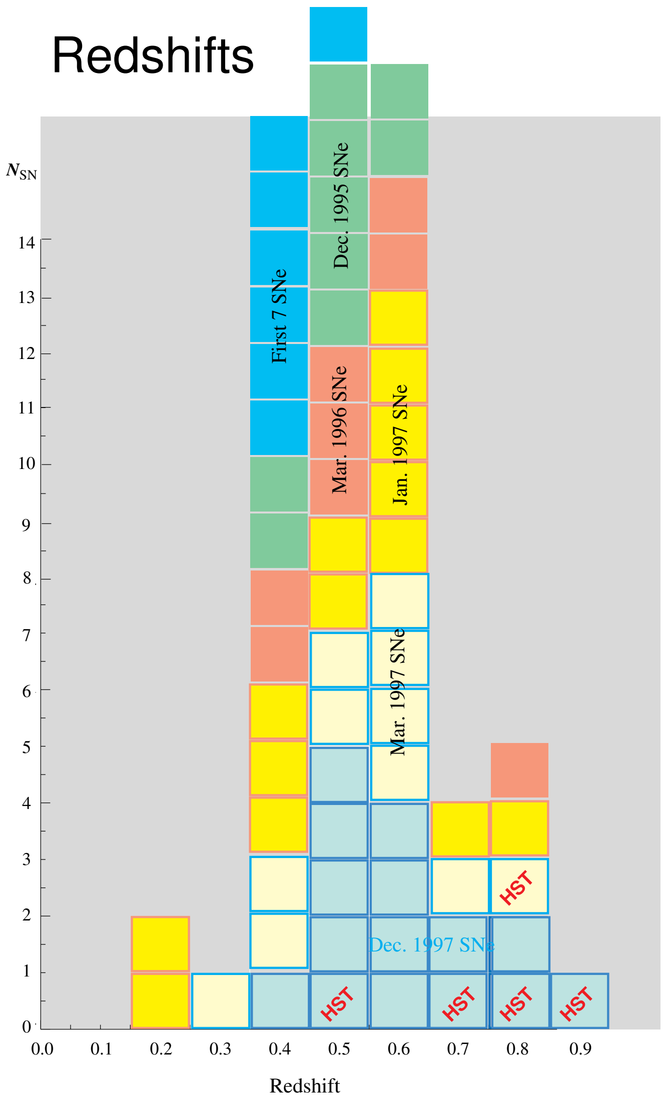


Perlmutter, *et al.*, Nature (1998)

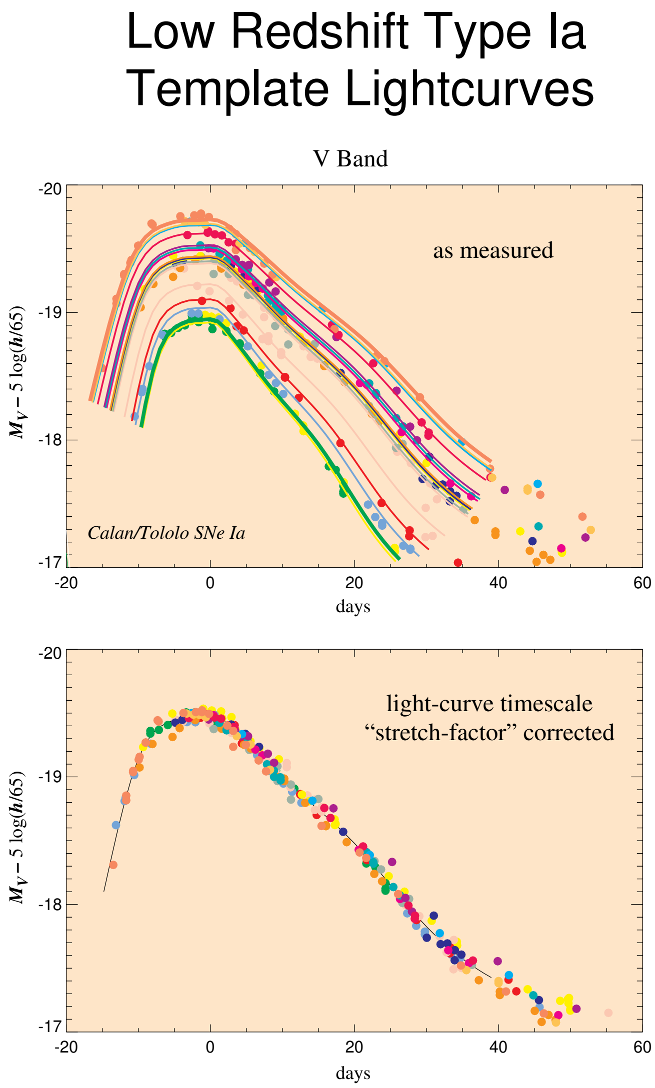
As a Type Ia supernova brightens and fades, its spectrum changes, showing on each day which elements in the expanding atmosphere are passing through the photosphere. This provides a rather tight constraint on the high-redshift supernova spectra: they must show all of the same features on the same day of the explosion as nearby Type Ia supernovae, or else we have evidence that the Type Ia supernovae have evolved over the 4-to-7 billion years that we are studying So far, we have seen no indications of evolution, even as far back in time as the highest redshift Type Ia supernova spectrum, shown on the right plot above in its place in the time sequence of "nearby" Type Ia supernova spectra. Note that the spectra are almost all observed with the Keck 10-m Telescope, a necessity for these very faintest supernovae.

http://www-supernova.lbl.gov/

C. Pennypacker
M. DellaValle, *Univ. of Padova*
R. Ellis, R. McMahon, *IoA, Cambridge*
B. Schaefer, *Yale University*
P. Ruiz-Lapuente, *Univ. of Barcelona*
H. Newberg, *Fermilab*

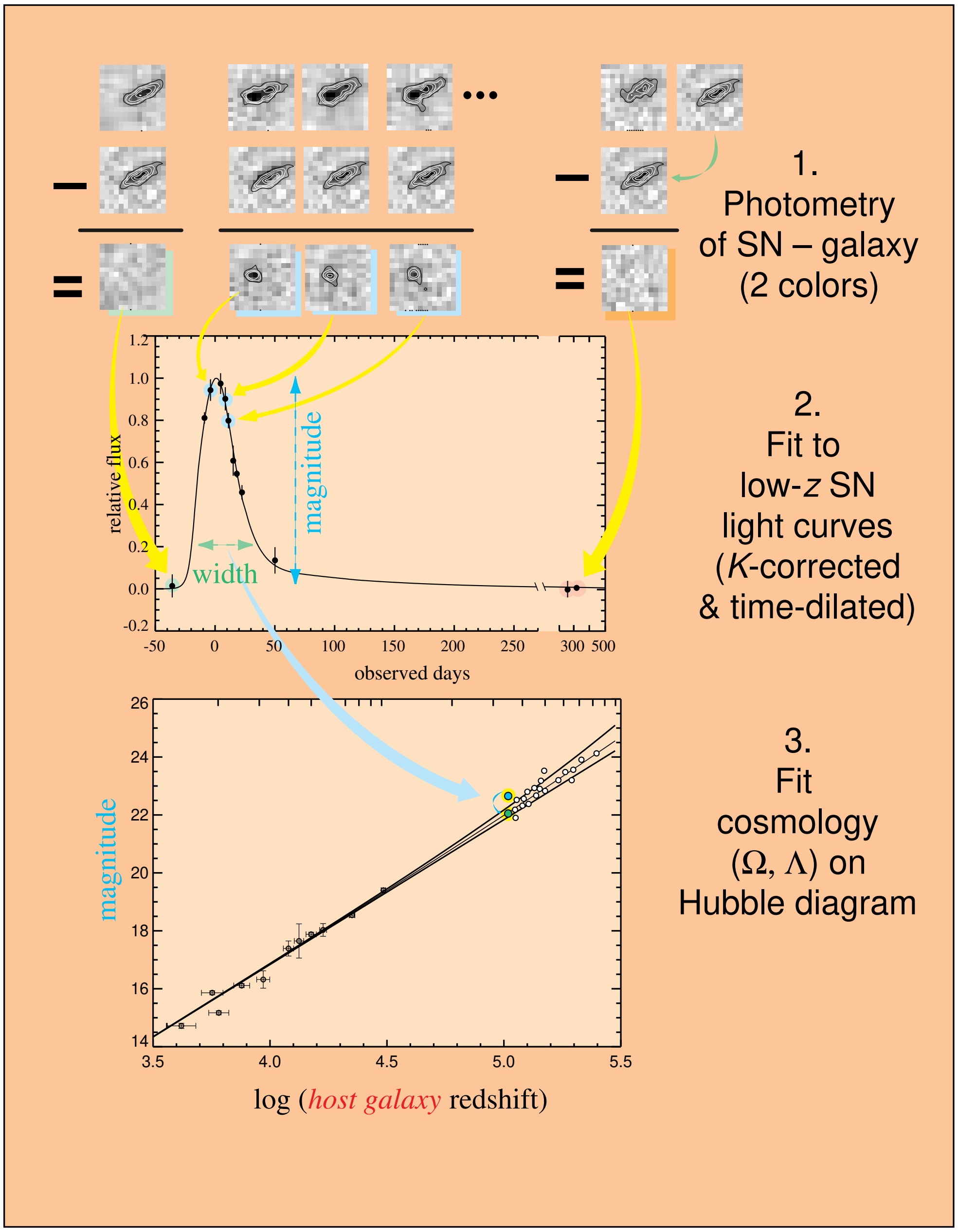


We have discovered well over 50 high redshift Type Ia supernovae so far. Of these, approximately 50 have been followed with spectroscopy and photometry over two months of the light curve. The redshifts shown in this histogram are color coded to show the increasing depth of the search with each new "batch" of supernova discoveries. The most recent supernovae, discovered the last week of 1997, are now being followed over their lightcurves with ground-based and (for those labeled "HST") with the Hubble Space Telescope.



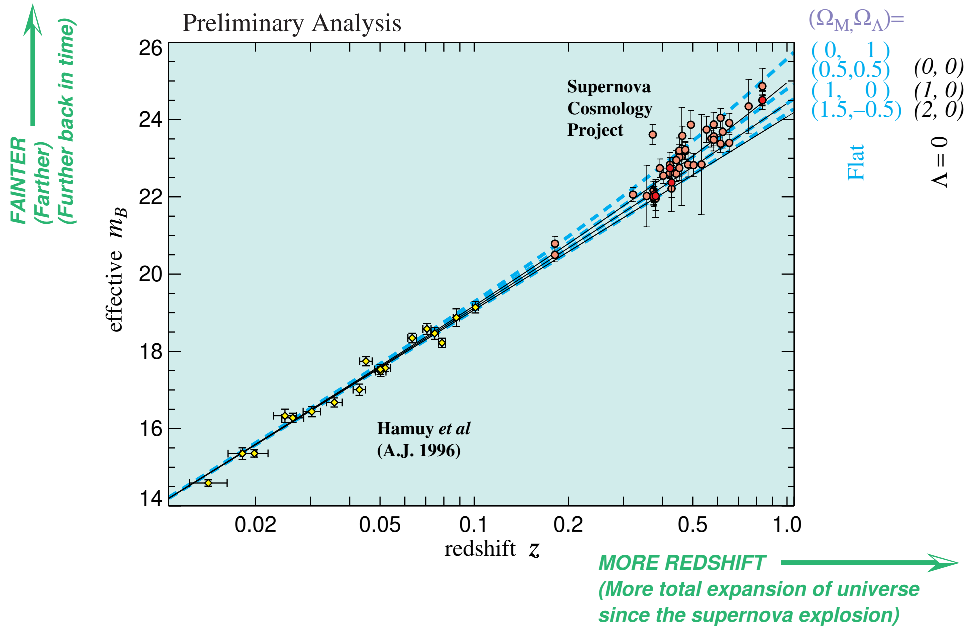
Type Ia supernovae observed "nearby" show a relationship between their peak absolute luminosity and the timescale of their light curve: the brighter supernovae are slower and the fainter supernovae are faster (see Phillips, *Ap.J.Lett.*, 1993 and Riess, Press, & Kirshner, *Ap.J.Lett.*, 1995). We have found that a simple linear relation between the absolute magnitude and a "stretch factor" multiplying the lightcurve timescale fits the data quite well until over 45 restframe days past peak. The lower plot shows the "nearby" supernovae from the upper plot, after fitting and removing the stretch factor, and "correcting" peak magnitude with this simple calibration relation.

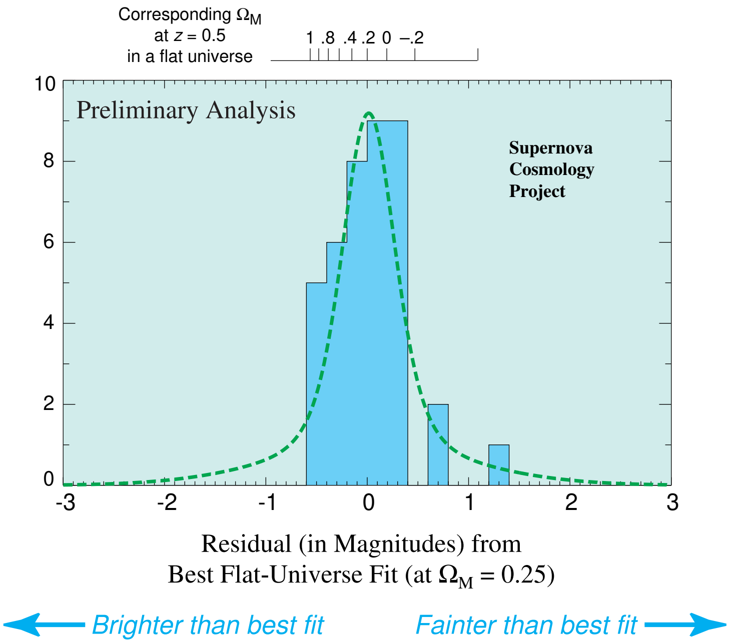
Analysis Steps



The supernovae are analyzed in the following three steps: First, the final image of the host galaxy alone is subtracted from the many images of each supernova spanning its lightcurve. The resulting *R*- and *I*-band photometry points are then fit to *K*-corrected (see Kim, Goobar, & Perlmutter, *P.A.S.P.* 1996) and (1+*z*)-time-dilated *B*- and *V*-band template SN Ia lightcurves. This fit yields the apparent magnitude at peak and the best fit "stretch factor" that indicates the timescale (and hence the intrinsic luminosity) of each supernova. Finally, all of the supernova magnitudes—corrected for the stretch-luminosity relation—are plotted on the Hubble diagram as a function of their host galaxy redshift (when available, or supernova redshift, when not). The magnitudes vs. redshifts can then be fit to various alternative cosmologies. We fit the two "favorite" one-dimensional cases, the flat ($\Omega_M + \Omega_\Lambda = 1$) universe, and the $\Lambda = 0$ universe, as well as solving for a confidence region in the Ω_M-vs-Ω_Λ plane.

Hubble Plots



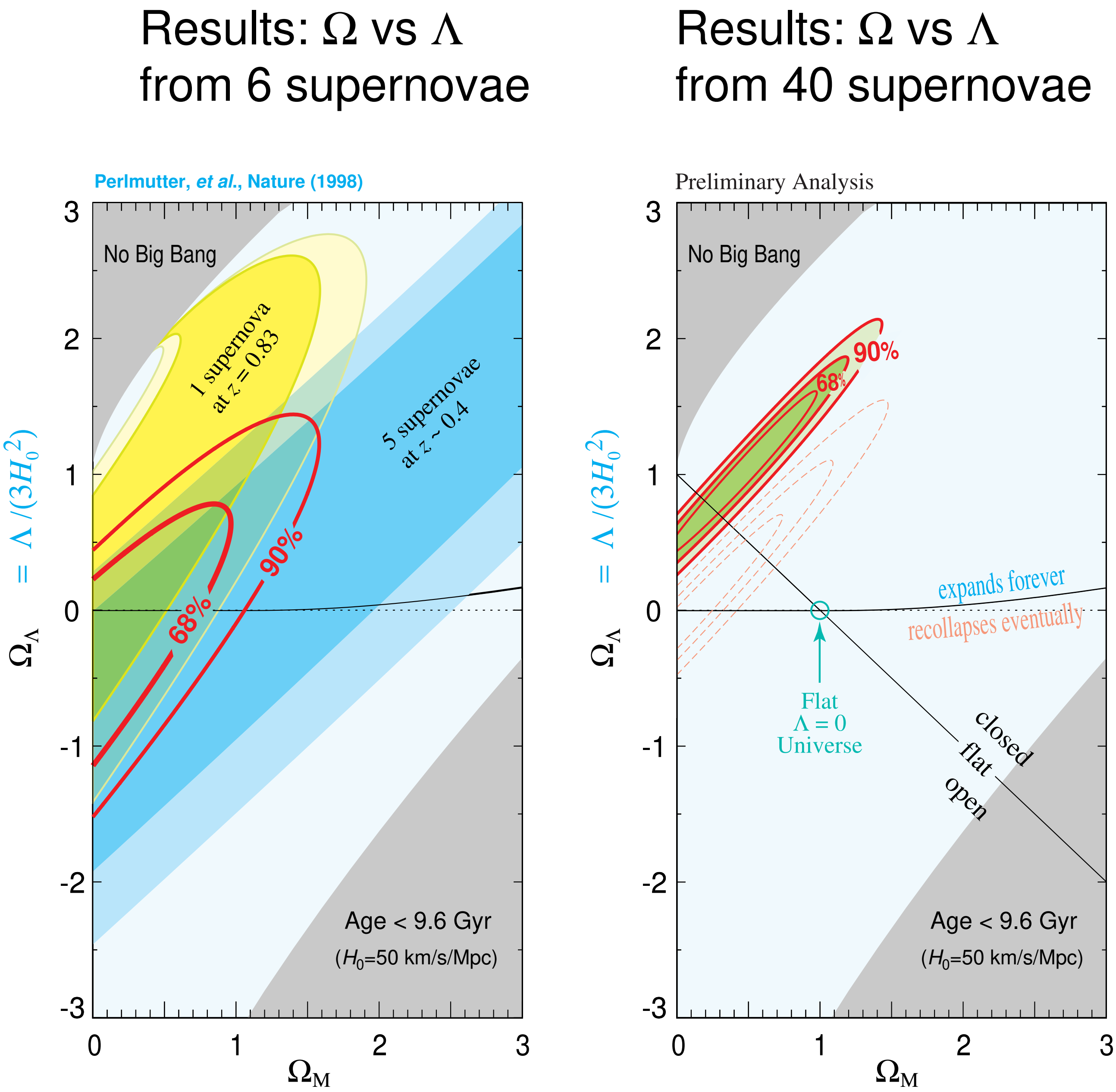


The Hubble diagram with the data from the supernovae already published (Perlmutter *et al, Ap.J.*, 1997, with the supernovae at $z \sim 0.4$, and Perlmutter *et al., Nature*, 1998, with the supernova at $z = 0.83$) shown as dark red circles with black outlines, and the next 35 supernovae shown as lighter red circles. The four dashed blue curves show the locus expected for a flat universe for four values of Ω_M (listed at right), and the three solid black curves are for a $\Lambda = 0$ universe. The lower plot is a histogram of residuals from the best fit values:

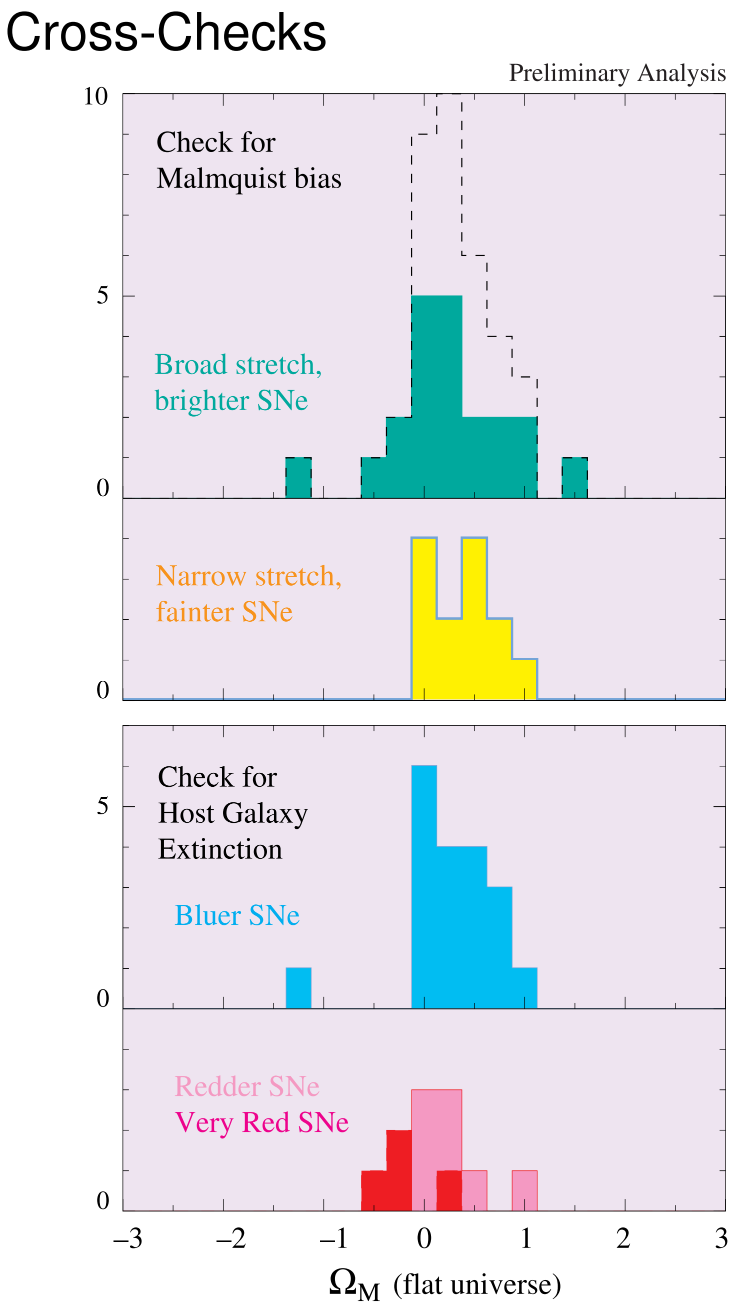
Flat universe: $\Omega_M = 0.25$ [± 0.06 statistical] [± 0.3 systematic]

$\Lambda = 0$ universe: $\Omega_M = -0.4$ [± 0.1 statistical] [± 0.5 systematic]

The green dashed curve shows the distribution of residuals from this flat-universe fit expected, given the statistical uncertainties on the supernova apparent magnitudes (primarily due to sky-background photon noise). The systematic uncertainty quoted corresponds to a 0.2 magnitude uncertainty.



These two plots show the best-fit confidence regions on the Ω_M-vs-Ω_Λ plane for the 6-supernova fit presented in the *Nature* (1998) paper and for a more extensive 40-supernova fit (preliminary analysis). The left plot demonstrates that with a range of redshifts from 0.4 to 0.85, the approximately straight slope of the confidence region at a given redshift begins to rotate, allowing an intersection region (shown in green) to isolate measurements of Ω_M and Ω_Λ separately, not just in linear combination (see Goobar & Perlmutter, *Ap.J.* 1995). With the larger sample of supernovae shown on the right plot, the statistical uncertainty is now small enough—and the confidence regions narrow enough—that the systematic uncertainty is the dominant source of error. The dashed-line confidence region on the right plot shows our preliminary estimate of this systematic uncertainty (shown in the direction of 0.2 lower apparent magnitudes for the high redshift supernovae). Further analysis should reduce this uncertainty. The best-fit confidence region (in green on the right plot) is centered at $\Omega_M = 0.5$, $\Omega_\Lambda = 1.0$. This confidence region lies along the line of $\Omega_\Lambda = \Omega_M + 0.5$, which is *not* parallel to the lines of constant deceleration $q_0 = \Omega_M/2 - \Omega_\Lambda$. Note that the confidence regions do not include the "standard model" inflationary universe with no cosmological constant (shown as a green circle at the intersection of the flat-universe line and the $\Lambda = 0$ line). The confidence regions do suggest that we live in a universe that will expand forever.



We check our results for a variety of possible systematic errors, including Malmquist bias and host-galaxy extinction (see Perlmutter *et al, Ap.J.* 1997 for a more extensive list and a discussion of techniques for cross-checking). By separating our supernovae into subsamples according to different parameters, we can test to see if that parameter is biasing our measurement. For example, to test for Malmquist bias, we plot the distribution of measurements of Ω_M for the intrinsically brighter supernovae in our sample—those with broader stretched lightcurves—and compare it to the distribution found for the intrinsically fainter supernovae in our sample—those with narrow lightcurves. The two distributions are not significantly shifted from each other, indicating that Malmquist bias is not a statistically significant error for this sample. (We assign a 0.15 systematic error as a conservative upper bound on any shift between the means of these distributions.) Similarly, there is no statistically significant shift between the redder and bluer supernovae in our sample, and we assign a 0.2 systematic error as an upper bound for extinction bias. Note that the very reddest of supernovae of our sample do show evidence of extinction, as they fall on the faint (low Ω_M side of the distribution), and are excluded in this study.