Discovery of a Supernova Explosion at Half the Age of the Universe and its Cosmological Implications

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The ultimate fate of the universe, infinite expansion or a big crunch, can be determined by measuring the redshifts, apparent brightnesses, and intrinsic luminosities of very distant supernovae. Recent developments have provided tools that make such a program practicable: (1) Studies of relatively nearby Type Ia supernovae (SNe Ia) have shown that their intrinsic luminosities can be accurately determined[1,2,3]; (2) New research techniques[4] have made it possible to schedule the discovery and follow-up observations of distant supernovae, producing well over 50 very distant ($z = 0.3 - 0.7$) SNe Ia to date[5,6,7]. These distant supernovae provide a record of changes in the expansion rate over the past several billion years. By making precise measurements of supernovae at still greater distances, and thus extending this expansion history back far enough in time, we can even distinguish[8] the slowing caused by the gravitational attraction of the universe's mass density Ω_M from the effect of a possibly inflationary pressure caused by a cosmological constant Λ. We report here the first such measurements, with our discovery of a Type Ia supernova (SN 1997ap) at $z = 0.83$. Measurements at the Keck II 10-m telescope make this the most distant spectroscopically confirmed supernova. Over two months of photometry of SN 1997ap with the Hubble Space Telescope and ground-based telescopes, when combined with previous measurements[2,5] of nearer SNe Ia, suggests that we may live in a low mass-density universe. Further supernovae at comparable distances are currently scheduled for ground and space-based observations.

SN 1997ap was discovered by the Supernova Cosmology Project on 5 March 1997 UT, during a two-night search at the CTIO 4-m telescope that yielded 16 new supernovae. The search technique finds such sets of high-redshift supernovae on the rising part of their light curves and guarantees the date of discovery, thus allowing follow-up photometry and spectroscopy of the transient supernovae to be scheduled[4]. The supernova light curves were followed with scheduled R-, I-, and some B-band photometry at the CTIO, WIYN, ESO 3.6m, and INT telescopes, and with spectroscopy at the ESO 3.6 m and Keck II telescopes. In addition, SN 1997ap was followed with scheduled photometry on the Hubble Space Telescope (HST).

Figure 1 shows the spectrum of SN 1997ap, obtained on 14 March 1997 UT with a 1.5 hour integration on the Keck II 10-m telescope. There is negligible ($\leq$5%) host-galaxy light contaminating the supernova spectrum, as measured from the ground- and space-based images. When fit to a time series of well-measured nearby Type Ia supernova (SN Ia) spectra[9], the spectrum of SN 1997ap is most consistent with a "normal" SN Ia at $z = 0.83$ observed 2 ± 2 SN-restframe days ($\sim$4 observer's days) before the supernova's maximum light in the restframe B band. It is a poor match to the "abnormal" SNe Ia, such as the brighter SN 1991T or the fainter SN 1986G. For comparison, the spectra of low-redshift, "normal" SNe Ia are shown with wavelengths redshifted as they would appear at $z = 0.83$. These spectra show the time evolution from seven days before to two days after maximum light.

Figure 2 shows the photometry data for SN 1997ap, with significantly smaller error bars for the HST observations (Figure 2a) than for the ground-based observations (Figure 2b and 2c). The width of a SN Ia's light curve has been shown to be an excellent indicator of its intrinsic luminosity, both at low redshift[1,2,3] and at high redshift[5]: the broader and slower the light curve, the brighter the supernova is at maximum. We characterize this width by fitting the photometry data to a "normal" SN Ia template light curve that has its time axis stretched or compressed by a linear factor, called the "stretch factor"[4,5]; a "normal" supernova such as SN 1989B, SN 1993O, or SN 1981B in Figure 1 thus has a stretch factor of $s \approx 1$. To fit the photometry data for SN 1997ap, we use template U- and B-band light curves that have first been $1+z$ time-dilated and wavelength-shifted ("K-corrected") to the R- and I-bands as they would appear at $z = 0.83$ (see ref 5 and Nugent et al in preparation). The best-fit stretch factor for all the photometry of Figure 2 indicates that SN 1997ap is a "normal" SN Ia: $s = 1.03 \pm 0.05$ when fit for a date of maximum at 16.3 March 1997 UT (the error-weighted average of the best-fit dates from the light curve, 15.3 ± 1.6 March 1997 UT, and from the spectrum, 18 ± 3 March 1997 UT).

It is interesting to note that we could alternatively fit the $1+z$ time dilation of the event, holding the stretch factor constant at $s = 1.0^{+0.05}_{-0.14}$, the best fit value from the spectral features obtained in ref 10. We find that the event lasted $1+z = 1.86^{+0.31}_{-0.09}$ times longer than a nearby $s = 1$ supernova, providing the strongest confirmation yet of the cosmological nature of redshift[11,12,9].

The best-fit peak magnitudes for SN 1997ap are $I = 23.20 \pm 0.07$ and $R = 24.10 \pm 0.09$. (In this letter, all magnitudes quoted or plotted are transformed to the standard Cousins[13] R and I bands.) These peak magnitudes are relatively insensitive to the details of the fit: if the date of maximum is left unconstrained or set to the date indicated by the best-match spectrum, or if the ground- and space-based data are fit alone, the peak magnitudes still agree well within errors.

The ground-based data show no evidence of host-galaxy light, but the higher-resolution HST imaging shows a marginal detection (after co-adding all four dates of observation) of a possible $m_I = 25.2 \pm 0.3$ host galaxy 1 arcsecond from the supernova. This light does not contaminate the supernova photometry from the HST and it contributes negligibly to the ground-based photometry. The projected separation is ~6 kpc (for $\Omega_{\rm M} = 1, \Omega_\Lambda = 0$, and $h_0 = 65$) and the corresponding B-band rest-frame magnitude is $M_B \sim -17$ and its surface brightness is $\mu_B \sim 21$ mag arcsec^{-2}, consistent with properties of local spiral galaxies. We note that the analysis will need a final measurement of any host-galaxy light after the supernova has faded, in the unlikely event that there is a very small knot of host-galaxy light directly under the HST image of SN 1997ap.

We compare the K-corrected $R - I$ observed difference of peak magnitudes (measured at the peak of each band, not the same day) to the $U - B$ color found for "normal" low-redshift SNe Ia. We find that the $(U - B)_{\rm SN1997ap} = -0.28 \pm 0.11$ restframe color of SN 1997ap is consistent with an unreddened "normal" SN Ia color, $(U - B)_{\rm normal} = -0.32 \pm 0.12$ (see ref 14 and also Nugent et al. in preparation). In this region of the sky, there is also no evidence for Galactic reddening[15]. Given the considerable projected distance from the putative host galaxy, the supernova color, and the lack of galaxy contamination in the supernova spectrum, we proceed with an analysis under the hypothesis that the supernova suffers negligible host-galaxy extinction, but with the following caveat:

Although correcting for $E(U\text{-}B) \approx 0.04$ of reddening would shift the magnitude by only one standard deviation, $A_B = 4.8E(U - B) = 0.19 \pm 0.78$, the uncertainty in this correction would then be the most significant source of uncertainty for this one supernova, due to the large uncertainty in the $(U - B)_{\rm SN1997ap}$ measurement and to the sparse low-redshift U-band reference data. HST J-band observations are currently planned for future $z > 0.8$ supernovae, to allow a comparison with the restframe $B - V$ color, a much better indicator of reddening for SNe Ia. Such data will thus provide an important improvement in extinction correction uncertainties for future SNe and eliminate the need for assumptions regarding host-galaxy extinction. In the following analysis, we also do not correct the lower-redshift supernovae for possible host-galaxy extinction, so any similar distribution of extinction would partly compensate for this possible bias in the cosmological measurements.

The significance of SNe Ia at $z = 0.83$ for measurements of the cosmological parameters is illustrated on the Hubble diagram of Figure 3. To compare with low-redshift magnitudes, we plot SN 1997ap at an effective restframe B-band magnitude of $B = 24.50 \pm 0.15$, derived, as in ref 5, by adding a K-correction and increasing the error bar by the uncertainty due to the (small) width-luminosity correction and by the intrinsic dispersion remaining after this correction. By studying SNe Ia at twice the redshift of our first previous sample at $z \sim 0.4$, we can look for a correspondingly larger magnitude difference between the cosmologies considered. At the redshift of SN 1997ap, a flat $\Omega_{\rm M} = 1$ universe is separated from a flat $\Omega_{\rm M} = 0.1$ universe by almost one magnitude, as opposed to half a magnitude at $z \sim 0.4$. For comparison, the uncertainty in the peak magnitude of SN1997ap is only 0.15 mag, while the intrinsic dispersion amongst stretch-calibrated SNe Ia is ~ 0.17 mag[5]. Thus, at such redshifts even individual SNe Ia become powerful tools for discriminating amongst various world models, provided observations are obtained, such as those presented here, where the photometric errors are below the intrinsic SNe Ia dispersion.

By combining such data spanning a large range of redshift, it is also possible to distinguish between the effects of mass density $\Omega_{\rm M}$ and cosmological constant Λ on the Hubble diagram[8]. The blue contours of Figure 4 show the allowed confidence region on the Ω_Λ ($\equiv \Lambda/(3H_0^2)$) versus $\Omega_{\rm M}$ plane for the $z \sim 0.4$ supernovae[5]. The yellow contours show the confidence region from SN 1997ap by itself, demonstrating the change in slope of the confidence region at higher redshift. The red contours show the result of the combined fit, which yields a closed confidence region in the Ω_M-Ω_Λ plane. This fit corresponds to a value of $\Omega_M = 0.6 \pm 0.2$ if we constrain the result to a flat universe ($\Omega_\Lambda + \Omega_M = 1$), or $\Omega_M = 0.2 \pm 0.4$ if we constrain the result to a $\Lambda = 0$ universe. These results are preliminary evidence for a relatively low-mass-density universe. The addition of SN 1997ap to the previous sample of lower redshift supernovae decreases the best fit Ω_M by approximately one standard deviation compared to the earlier results[5].

Our data for SN 1997ap demonstrate (1) that SNe Ia at $z > 0.8$ exist, (2) that they can be compared spectroscopically with nearby supernovae to determine SNe ages and luminosities and check for indications of supernova evolution, and (3) that calibrated peak magnitudes with precision better than the intrinsic dispersion of SNe Ia can be obtained at these high redshifts. The width of the confidence regions in Figure 4 and the size of the corresponding projected measurement uncertainties show that with additional SNe Ia having data of quality comparable to SN1997ap a simultaneous measurement of Ω_Λ and Ω_M is possible. It is important to note that this measurement is based on only one supernova at the highest ($z > 0.8$) redshifts, and that a larger sample size is required to find a statistical peak and identify any "outliers." In particular, SN 1997ap was discovered near the search detection threshold and thus may be drawn from the brighter tail of a distribution ("Malmquist bias"). There is similar potential bias in the lower-redshift supernovae of the Calán/Tololo survey, making it unclear which direction such a bias would change Ω_M.

Several more supernovae at comparably high redshift have already been discovered by the Supernova Cosmology Project, including SN 1996cl, also at $z = 0.83$. SN 1996cl can be identified as a very probable SN Ia, since a serendipitous HST observation (Donahue et al., private communication) shows its host galaxy to be an elliptical or S0. Its magnitude and color, although much more poorly constrained by photometry data, agree within uncertainty with those of SN 1997ap. The next most distant spectroscopically confirmed SNe Ia are at $z = 0.75$ and $z = 0.73$[16] (these supernovae are awaiting final calibration data). In the redshift range $z = 0.3 - 0.7$, we have discovered over 30 additional spectroscopically confirmed SNe Ia, and followed them with two-filter photometry. (The first sample of $z \sim 0.4$ SNe were not all spectroscopically confirmed and observed with two-filter photometry[5].) These new supernovae will improve both the statistical and systematic uncertainties in our measurement of $\Omega_{\rm M}$ and Ω_Λ in combination. A matching sample of $\geq$6 SNe Ia at $z > 0.7$ is to be observed in two filters with upcoming Hubble Space Telescope observations. SN1997ap demonstrates the efficacy of these complementary higher redshift measurements in separating the contribution of $\Omega_{\rm M}$ and Ω_Λ.

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Acknowledgements: We would like to thank CTIO, Keck, HST, WYIN, ESO and the ORM – La Palma observatories for a generous allocation of time and the support of dedicated staff in pursuit of this project. Dianne Harmer, Paul Smith and Daryl Willmarth were extraordinarily helpful as WIYN queue observers. We would especially like to thank

Gary Bernstein and Tony Tyson for developing and supporting the Big Throughput Camera which was instrumental in the discovery of this supernova.

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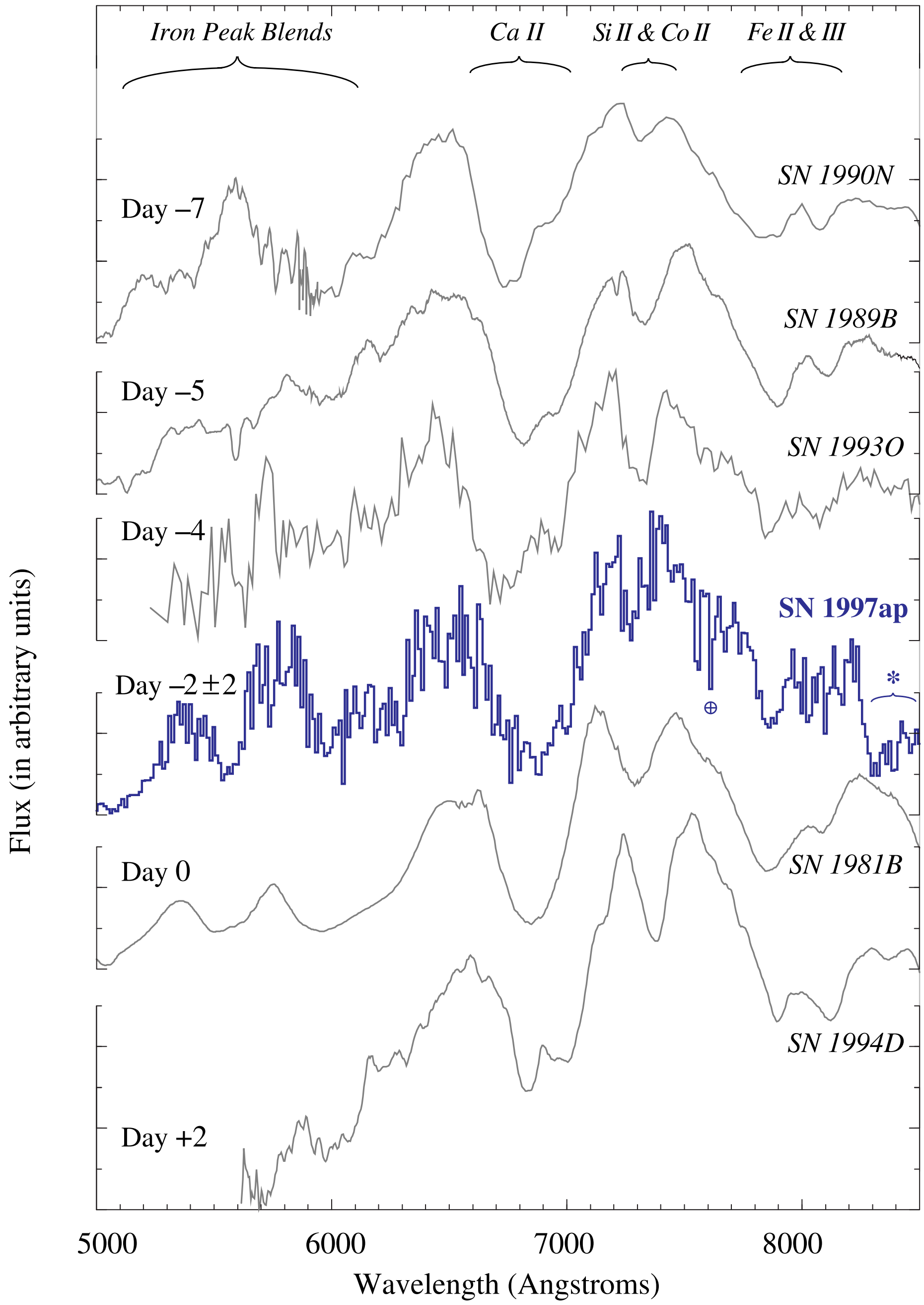

Figure 1: Spectrum of SN 1997ap, after binning by 12.5 Å, placed within a time series of spectra of "normal" SNe Ia [17,18,19,20,21] (the spectrum of SN 1993O was provided courtesy of the Calán/Tololo Supernova Survey), as they would appear redshifted to $z = 0.83$. The spectra show the evolution of spectral features between 7 restframe days before and 2 days after restframe B-band maximum light. SN 1997ap matches best at 2 ± 2 days before maximum light. The symbol $\oplus$ indicates an atmospheric absorption line and * indicates a region affected by night sky line subtraction residuals. The redshift of $z = 0.83 \pm 0.005$ was determined from the supernova spectrum itself, since there are no host galaxy lines detected.

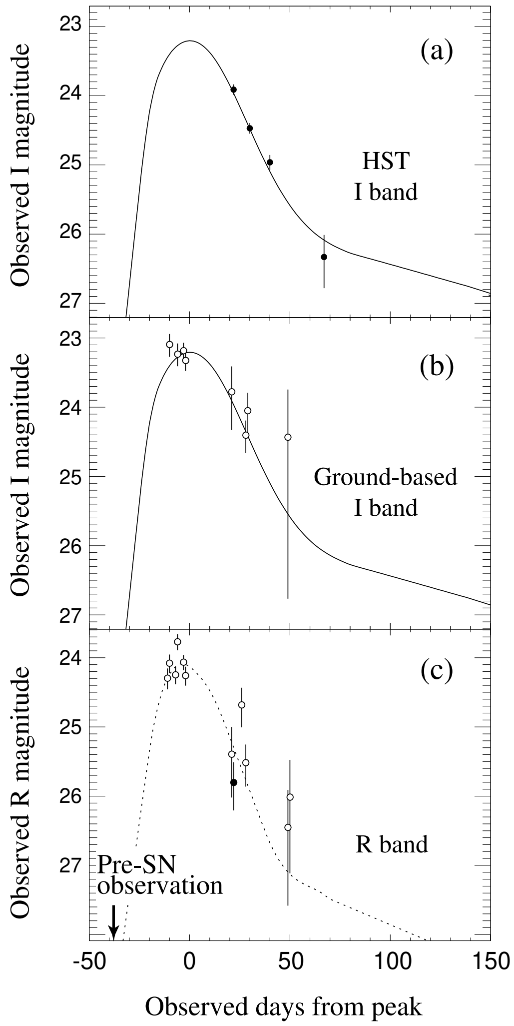

Figure 2: Photometry points for SN 1997ap (a) as observed by the HST in the F814W filter; (b) as observed with ground-based telescopes in the Harris I filter; and (c) as observed with the ground-based telescopes in the Harris R filter (open circles) and the HST in the F675W filter (filled circle); with all magnitudes corrected to the Cousins I or R systems[13]. The solid line shown in both (a) and (b) is the simultaneous best fit of the ground- and space-based data to the K-corrected, $(1+z)$ time-dilated Leibundgut B-band SN Ia template light curve[22], and the dotted line in (c) is the best fit to a K-corrected, time-dilated U band SN Ia template light curve. The ground-based data was reduced and calibrated following the techniques of ref 5, but with no host-galaxy light subtraction necessary. The HST data was calibrated and corrected for charge transfer inefficiency following the prescriptions of refs. 23 and 24. K-corrections were calculated as in ref 25, modified for the HST filter system. Correlated zeropoint errors are accounted for in the simultaneous fit of the lightcurve. The errors in the calibration, charge transfer inefficiency correction and K-corrections for the HST data are much smaller ($\sim$4% total) than the contributions from the photon noise. No corrections were applied to the HST data for a possible $\sim$4% error in the zeropoints (P. Stetson, private communication) or for non-linearities in the WFPC2 response[26], which might bring the faintest of the HST points into tighter correspondence with the best fit lightcurve in (a) and (c). Note that the individual fits to the data in (a) and (b) agree within their error bars, providing a first-order cross check of the HST calibration.

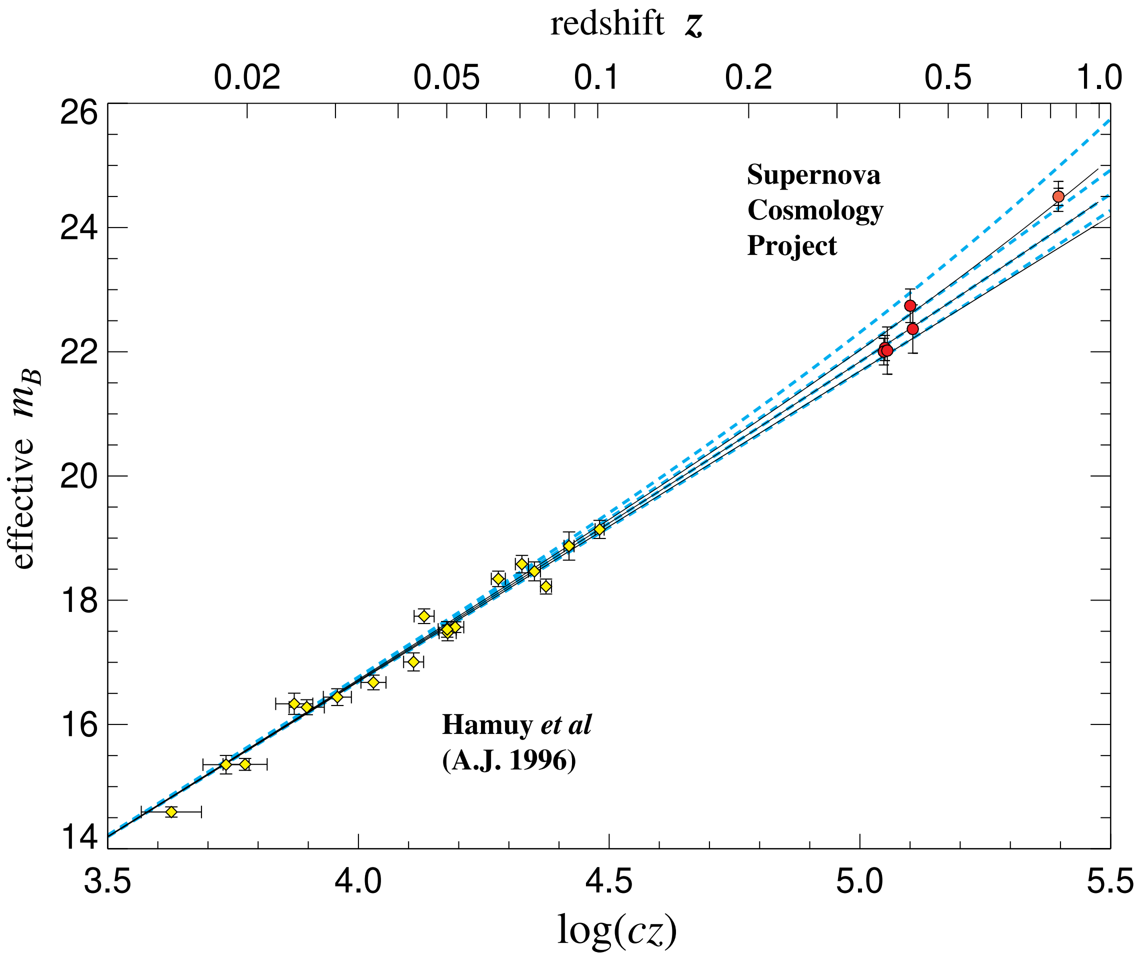

Figure 3: SN 1997ap at $z = 0.83$ plotted on the Hubble diagram from ref 5 with the five of the first seven high-redshift supernovae that could be width-luminosity corrected and the 18 of the lower-redshift supernovae from the Calán/Tololo Supernova Survey that were observed earlier then 5 days after maximum light. Magnitudes have been K-corrected and corrected for the width-luminosity relation. The inner error bar on the SN 1997ap point corresponds to the photometry error alone while the outer error bar includes the intrinsic dispersion of SNe Ia after stretch correction. The solid curves are theoretical m_B for $(\Omega_\mathrm{M}, \Omega_\Lambda) = (0, 0)$ on top, $(1, 0)$ in middle, and $(2, 0)$ on bottom. The dotted curves are for the flat universe case, with $(\Omega_\mathrm{M}, \Omega_\Lambda) = (0, 1)$ on top, $(0.5, 0.5)$, $(1, 0)$, and $(1.5, -0.5)$ on bottom.

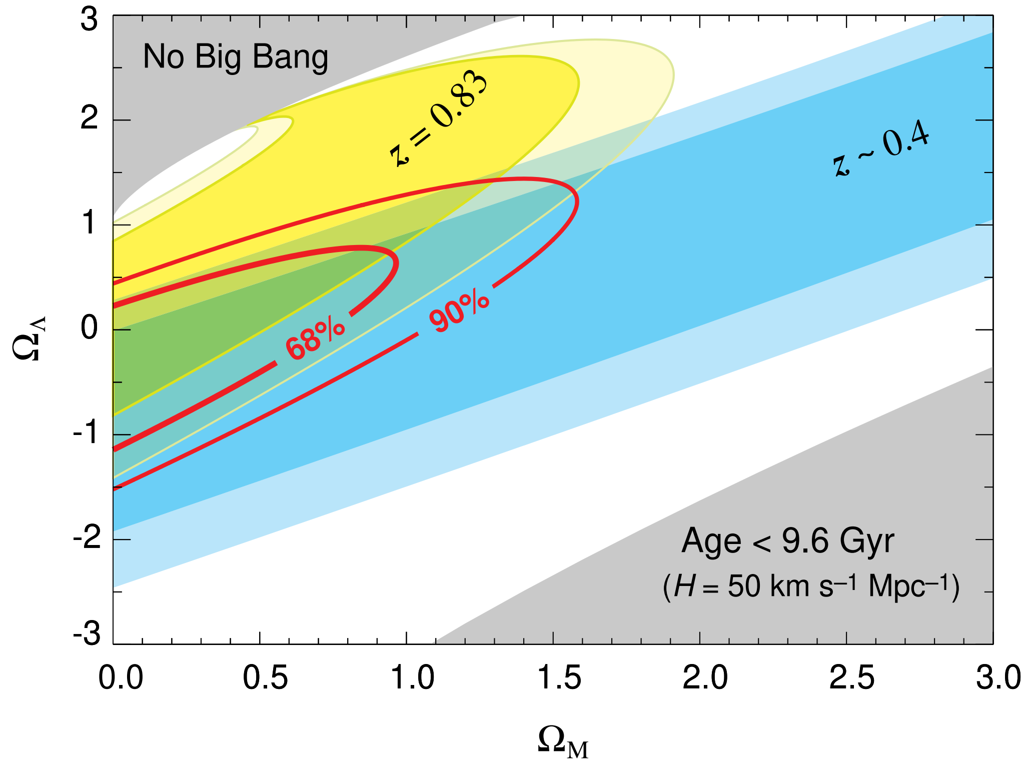

Figure 4: [*Color Version*] Contour plot of the 68% (1σ) and 90%, confidence regions in the Ω_Λ versus $\Omega_{\rm M}$ plane, for (blue shading) the five supernovae at $z \sim 0.4$ (see ref 5); (yellow shading) SN 1997ap at $z = 0.83$, and (red contours) all of these supernovae taken together. The two labeled corners of the plot are ruled out because they imply: (upper left corner) a "bouncing" universe with no big bang[27], or (lower right corner) a universe younger than the oldest heavy elements, $t_0 < 9.6$ Gyr[28], for any value of $H_0 \geq 50$ km s^{-1} Mpc^{-1}.

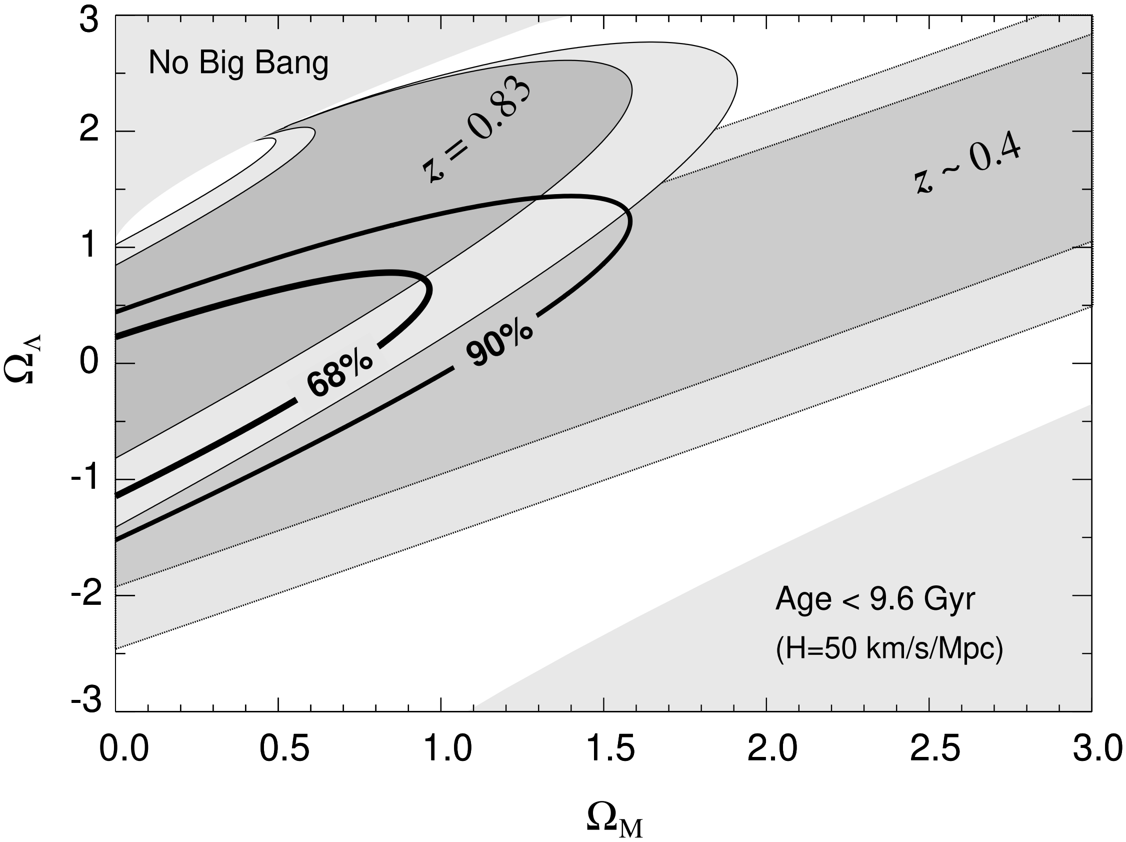

Figure 4: [*Black and White Version*] Contour plot of the 68% (1σ) and 90%, confidence regions in the Ω_Λ versus Ω_M plane, for the five supernovae at $z \sim 0.4$ (see ref 5), SN 1997ap at $z = 0.83$, and (shown as dark, unfilled contours) all of these supernovae taken together. The two labeled corners of the plot are ruled out because they imply: (upper left corner) a "bouncing" universe with no big bang[27], or (lower right corner) a universe younger than the oldest heavy elements, $t_0 < 9.6$ Gyr[28], for any value of $H_0 \geq 50$ km s^{-1} Mpc^{-1}.