Recent results from the Supernova Cosmology Project

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I report recent results from the Supernova Cosmology Project. We find observational evidence for an accelerating Universe and a positive cosmological constant from an analysis of 18 low-redshift and 42 high-redshift Type Ia supernovae. In a flat Universe, we derive a value of $\Omega_{\mathrm{M}} = 0.28^{+0.09}_{-0.08}\,{}^{+0.05}_{-0.04}$ for the mass density of the Universe,where the first uncertainty is statistical and the second includes systematic effects.

1 Principles of measurement

Within the FLRW[a] cosmological model, the following equation can be derived:

$$1 - \Omega_{\mathrm{k}} = \Omega_{\mathrm{M}} + \Omega_{\Lambda} \tag{1}$$

which express the fact that energy densities, $\Omega_{\mathrm{M}} \equiv 8\pi G/3H^2$ coming from matter and $\Omega_{\Lambda} \equiv \Lambda/3H^2$ coming from the cosmological constant, contribute to the curvature term $\Omega_{\mathrm{k}} \equiv k/a^2H^2$. H is the expansion rate or Hubble parameter, and a the cosmic scale factor.

The main goal of the *Supernova Cosmology Project* is to measure two of the fundamental cosmological parameters Ω_{M} and Ω_{Λ} at our present epoch. For that, a simple geometrical approach is used, based on the measurement of *luminosity distances,* using *standard candles* in the Universe. This distance, d_L, derived from the measurement of the apparent flux, $d_L^2 = \frac{\mathcal{L}}{4\pi F}$, is a function of the cosmological parameters H_0, Ω_{M}, Ω_{Λ} and the redshift z [2]. In a magnitude system, the relation between the apparent magnitude and the cosmological parameters writes

$$m(z) = M - 5\log H_0 + 25 + 5\log D_L(z;\Omega_{\mathrm{M}},\Omega_{\Lambda}) \tag{2}$$

where $D_L = H_0 d_L$ is the "Hubble constant free" luminosity distance and M the absolute magnitude of the *standard candle.*

[a] Friedman-Lemaître-Robertson-Walker

2 Type Ia SNe as calibrated candles

Since the earliest studies of supernovae, it has been suggested that these luminous events might be used as *standard candles* for cosmological measurements. So far only supernovae Ia[1] have shown homogeneity both in lightcurves and spectra, with a dispersion in the peak magnitude of $\sigma \sim 0.3$ to 0.5 mag, depending on the sample considered, making these events almost standard candles. Moreover, it was first shown by Phillips[18] that this class of SN can be described by a single parameter relating lightcurve width and peak magnitude. The broad, slow declining-lightcurve supernovae are brighter, while the narrow, fast declining-lightcurve supernovae are fainter. In the analysis, this property is described by using one single *stretch* parameter s which consists of stretching or compressing the time axis of the lightcurve template (see Figure 1). This simple parameterization gives variations on the lightcurve that fit the variety of SNe Ia both before and after maximum light and reduces the dispersion of the peak magnitude distribution to ~ 0.15 mag. This correction makes SNe Ia very good "calibrated candles" and therefore excellent tools for measuring the cosmological parameters.

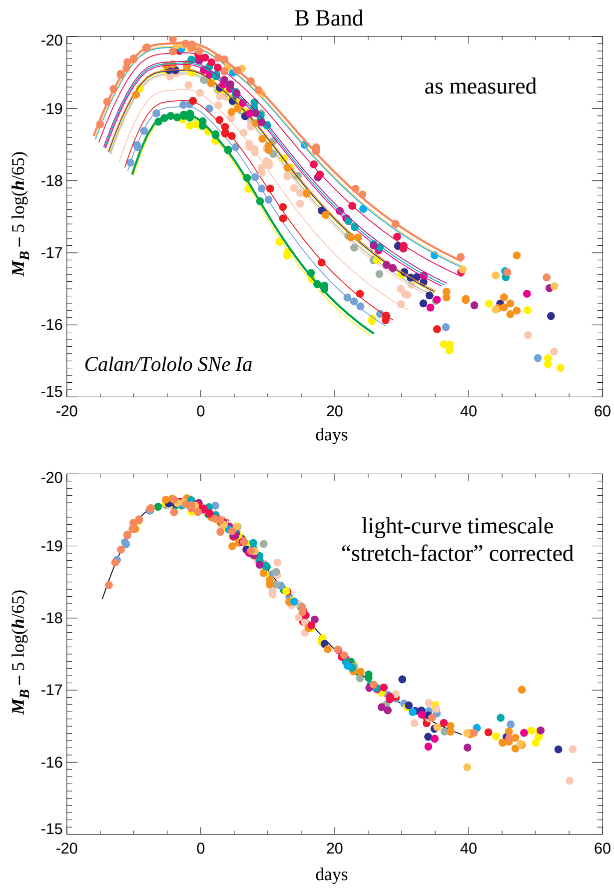

Figure 1: Lightcurves of about 10 well measured nearby supernovae discovered and followed-up by the Calan/Tololo survey: before the width-magnitude correction (top) and after correction using the "stretch factor" technique (bottom).

3 Detection/Follow-up of distant SNe

Supernovae at high redshift are difficult to work with for at least three reasons: they are rare, they are rapid, and they are random. The estimates of SN Ia rates—a few per millennium per galaxy—are daunting, if one wants a statistically useful sample of supernovae. Much of the interesting data must be obtained rapidly, since the supernova rises to maximum light within a few weeks and, at high redshifts, fades below the largest telescopes limits within a month or two. Furthermore, it is not possible to guarantee photometry and particularly spectroscopy of randomly occurring high-redshift supernovae, since the largest, most over-scheduled telescopes are needed to observe them. Ideally one would like to *schedule* supernova explosions on demand, and then apply for the telescope time to study them, beginning at least a few days before maximum light.

3.1 Search Strategy

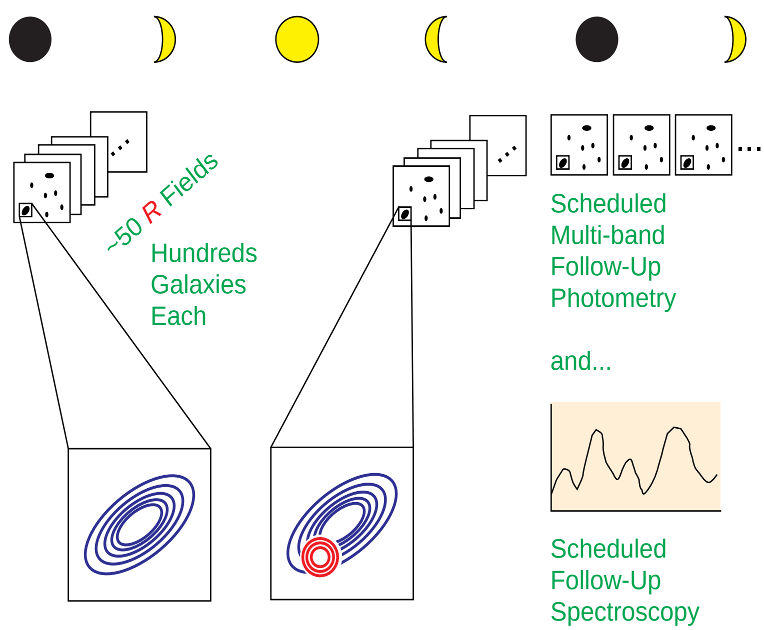

Figure 2: Search strategy designed to discover batches of ∼10 high-redshift supernovae on demand, just before new moon, and while the supernovae are still brightening, i.e. before "maximum light." The follow-up spectroscopy and photometry can therefore be scheduled, and can follow the supernovae over maximum light during dark time.

To solve these problems, new search techniques were developed. Figure 2 presents a schematic outline of the strategy. Just after a new moon, many tens of high-galactic-latitude fields (including known high-redshift clusters when possible) are observed on a 2.5- to 4-meter telescope. With a wide-field camera, each image contains hundreds of galaxies at high redshifts. Just before the following new moon, the same fields are observed again. The images are compared, thus checking tens of thousands of high redshift galaxies to find the ten or so showing the new light of a supernova that was not there on the previous observation. The supernovae generally do not have time to reach maximum light, with only 2.5 to 3 weeks (or approximately 11 to 14 days in the supernova rest frame) between our after- and before-new-moon comparison images. In order to begin the follow-up photometry and spectroscopy immediately, extensive software has been developed to make it possible to complete the analysis of all the images within hours of the observations.

In short, this search technique allows "batches" of pre-maximum-light supernova discoveries to be *scheduled* just before new moon, the ideal time to begin follow-up spectroscopy and photometry. This follow-up can now be scheduled as well, on the largest telescopes.

3.2 Analysis

The data analysis involves several stages which are summarized on Figure 3. The supernova light in each image must be measured and the underlying host galaxy light subtracted off. At these redshifts, the supernova seeing disk usually covers a significant amount of the galaxy, so it is important to do this step correctly. Each image has different seeing, and often a different telescope's point-spread-function (PSF) varies both spatially over the field and temporally over the course of an observing night. The amount of galaxy light that must be subtracted therefore varies from image to image.

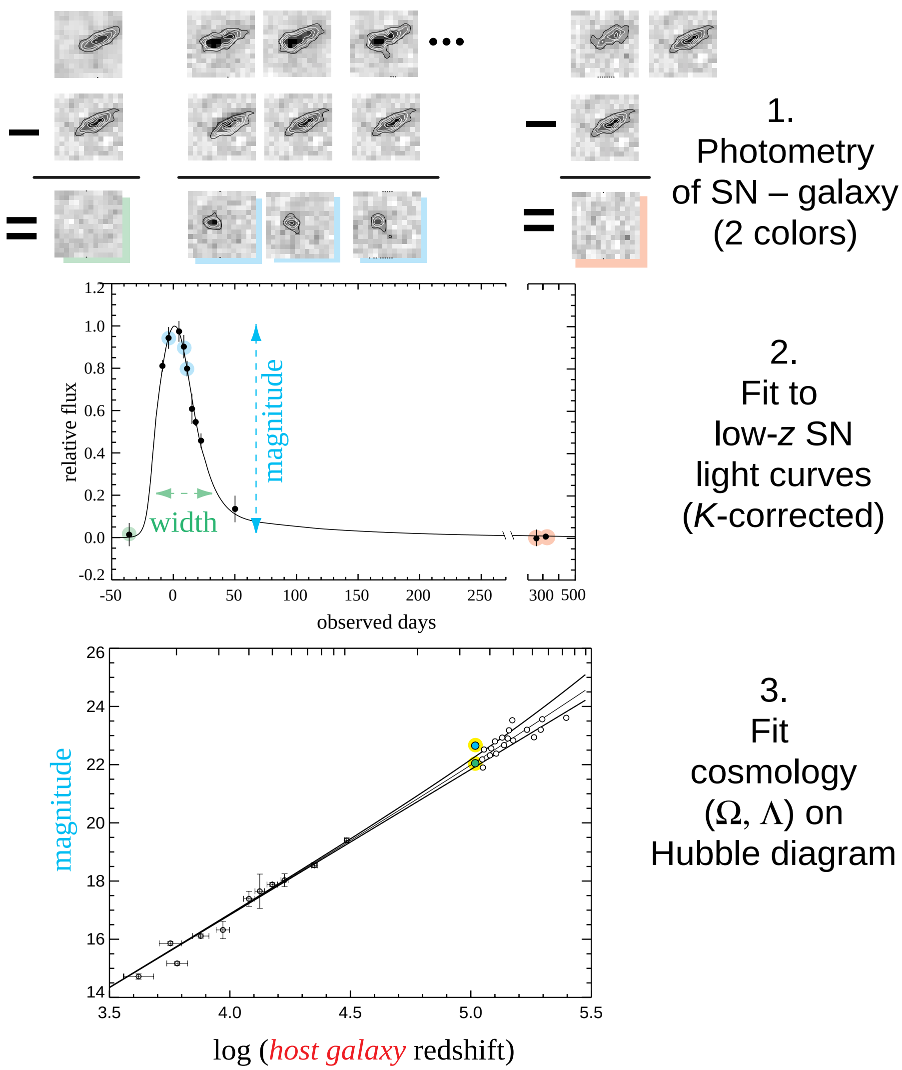

Figure 3: Data analysis stages: (1) reduction of the observed image data to individual photometry points. (2) comparison of these points with nearby SN Ia light curves to determine the luminosity distance and hence the cosmological parameters (3).

To compare the high-redshift supernova photometry points to nearby SN Ia light curves, it is necessary to calculate the K correction that accounts for the redshifting of the light observed in a given filter. The standard K corrections give the magnitude difference between the light emitted in a given filter band and the light observed after redshifting in that same band. Since at redshifts of order $z = 0.45$ the light received in the R band corresponds approximately to the light emitted in the B band, a generalization of the K correction, K_{RB}, is calculated that gives the magnitude difference between the rest frame B magnitude and the observed R magnitude[5].

The K-corrected time-dilated lightcurve template is then fitted to the data points and the peak magnitudes are derived. Finally, the cosmological parameters are extracted from a fit of the FLRW model to the peak magnitude vs redshift data.

4 Recent Results

Two international collaborations have started the extremely difficult task of measuring Ω_M and Ω_Λ using SNe Ia : the *Supernova Cosmology Project* (SCP) and the *High-Z Supernova Team* (HZT). They use similar techniques both for detecting high-redshift supernovae and to analyse them. Their first results were recently presented[17,7, 23,19].

The Supernova Cosmology Project, composed of both physicists and astronomers, started in 1988. Techniques were developped, including instrumentation, analysis, and observing strategies, that make it possible to systematically study high-redshift supernovae. As of December 1999, about 80 Type Ia supernovae at redshifts $z = 0.18$–1.2 have been discovered and studied[8,9, 10,11, 12,13,15]. Results presented here are based on the analysis of 42 high-z SNe together with 18 nearby SNe previously discovered in Chile by the Calan / Tololo Survey[7]. Figure 4 shows the Hubble diagram obtained.

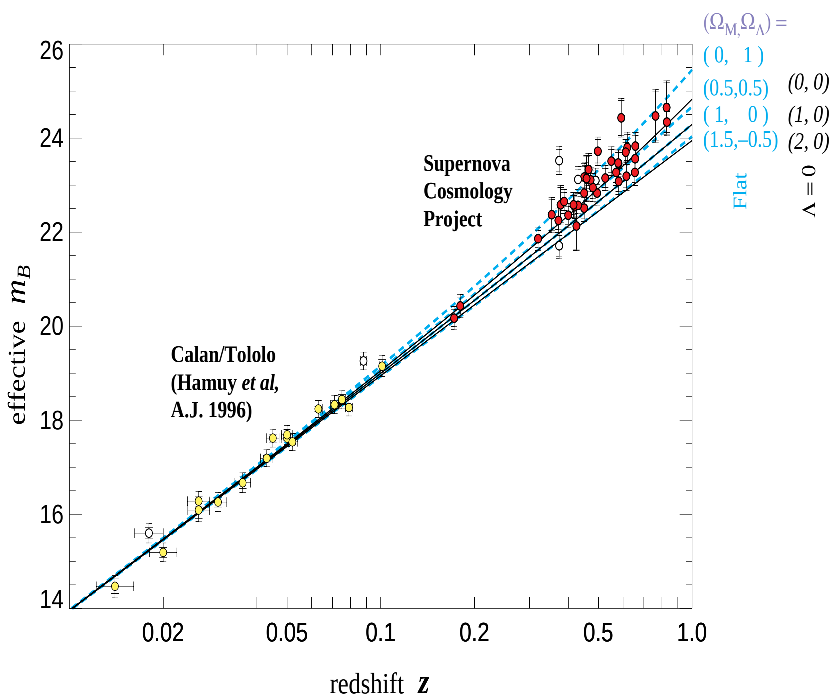

Figure 4: Hubble diagram for 42 high-redshift Type Ia supernovae from the Supernova Cosmology Project, and 18 low-redshift Type Ia supernovae from the Calán / Tololo Supernova Survey.

Confidence levels derived from a χ^2 fit of the cosmological parameters to the magnitude

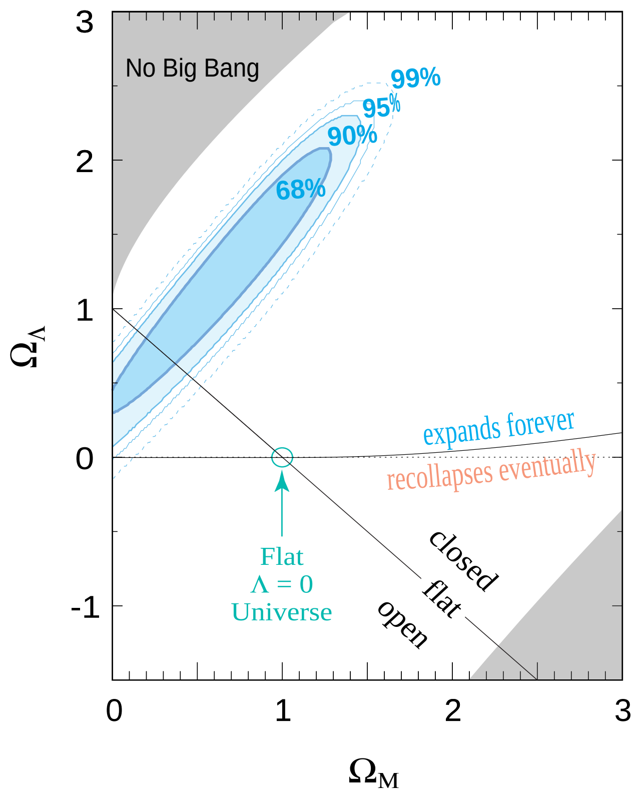

Figure 5: Supernova Cosmology Project best-fit confidence regions in the Ω_M–Ω_Λ plane

vs redshift plot are shown on Figure 5. The simplest inflationary model of $\Omega_M = 1$ and $\Omega_\Lambda = 0$ is more than 7σ away. A universe with zero cosmological constant is ruled out at the $\sim 3\sigma$ level and we are currenlty in an phase of acceleration of the expansion of the Universe. An independent measurements of Ω_M and Ω_Λ is not yet possible since it would require data at higher redshift and we obtain $\Omega_M = 0.28^{+0.09}_{-0.08}(stat.)^{+0.05}_{-0.04}(syst.)$ for a flat Universe ($\Omega_M + \Omega_\Lambda = 1$) therefore pointing to a low density Universe with a significant contribution from the cosmological constant.

5 Discussion

Given the potentially revolutionary nature of these results, it is important to carefully examine all possible sources of systematics. Both groups have gone through this with extreme care, studying possible systematics arising from extinction, sample selection or contamination effect, possible evolution of SNe Ia and lensing effects. So far, none of these effects can reconcile data with the $\Omega_M = 1, \Omega_\Lambda = 0$ solution and furthermore a non-zero Λ universe remains very likely for any value of Ω_M. Most sources of possible systematic errors will be studied in detail in the near future in various systematic searches for supernovae: low redfhift ($z < 0.1$) SNe to fully understand the supernova event and unbiased sample, high quality data on intermediate redshift($0.2 < z < 0.8$) SNe to trace evolution and high redshift($z \sim 1$) SNe to confirm the current results, possibly obtain more precise and independent measurement of Ω_M and Ω_Λ.

If confirmed, this result would be a first evidence for a non zero cosmological constant, Λ. Such a value for Λ poses various interesting questions related to particle physics. Why is Λ non zero and nevertheless so small ? is Λ a constant or did it vary in the course of the expansion of the Universe ? why is today's value of the mass density Ω_M so close to the value of the cosmological constant density Ω_Λ. Several authors have attempted to address these very important questions (see for example[25]) but new and more precise measurement of the comological parameters will be needed to further constraint these theories. Detection and follow-up of a few hundred of type Ia supernovae up to redshifts $z \sim 1$ would, for example, allow measuring the time variation of Λ[4]. Such a measurement would require doing a space experiment such as SNAP (SuperNova Acceleration Probe[24]) proposed by the Supernova Cosmology Project.

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