# IMPROVING COSMOLOGICAL CONSTRAINTS WITH NEW AND COMBINED SUPERNOVA DATASETS

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We present the results of an analysis of the world SNe data, complemented by a new dataset of low-redshift nearby-Hubble-flow SN Ia. This ”Union” compilation of more than 400 SN Ia includes the recent large samples of SNe Ia from the Supernova Legacy Survey and the ESSENCE Survey, the older datasets, as well as the recently extended dataset of distant supernovae observed with HST. A single, consistent and blind analysis procedure is used for all the various SN Ia subsamples. We present the latest results from this Union compilation and its combination with other cosmological measurements (CMB and BAO), and discuss the cosmological constraints on the dark energy density. With the addition of our new nearby Hubble-flow SNe Ia, these resulting cosmological constraints are currently the tightest available. While our results are consistent with a cosmological constant, we obtain only relatively weak constraints on an equation of state, $w$, that varies with redshift. The Union compilation data along with software for cosmological analysis is provided through the web link “http://supernova.lbl.gov/Union”.

## 1 Introduction

A decade after its discovery[1,2] and despite much progress in the field, dark energy still remains a mystery waiting to be resolved. Several new cosmological measurement techniques and several new Type Ia supernova (SN Ia) datasets allowed to narrow in on the properties of dark energy. The SN Ia measurements remain a key ingredient in all current determinations of cosmological parameters (see, e.g., the recent CMB results[3]). It is therefore necessary to understand how the current world dataset of SN Ia measurements is constructed, and how it can be used coherently, particularly since no one SN Ia sample by itself provides an accurate cosmological measurement.

We present a new SNe compilation for cosmological analysis, the “Union” compilation[4]. The Union compilation includes nearby SNe sets from a number of campaigns[5,6,7,8,9,10], and is complimented by a new data set of nearby SNe from the SCP Nearby 99 campaign[4]. The recent large high-redshift samples from the Supernova Legacy Survey (SNLS)[11] and ESSENCE[12] surveys, the set of distant SN observed with HST[13,14] as well as previous high redshift SN sets [15,16,17,1,2] have been included. The compilation comprises 414 SNe. In addition to being the largest SN data set to date, the SNe of the Union compilation where analysed in a uniform manner with careful control of systematic errors (see sections 2 and 3). In section 4 we present some of the new cosmological constraints obtained from the combination of the Union SN data set with observations of the cosmic microwave background (CMB) and baryon acoustic oscillations (BAO).

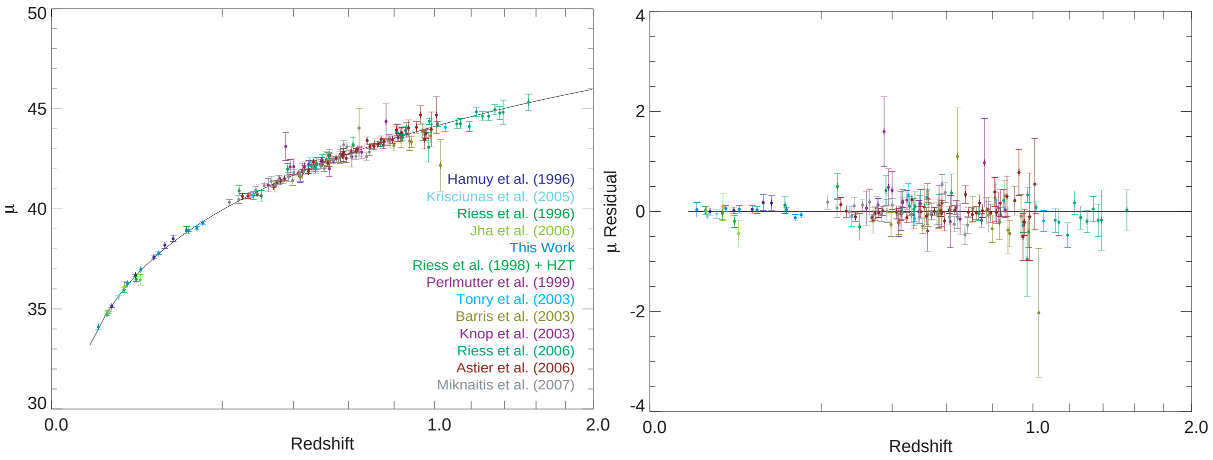

Figure 1: *Left:* Binned Hubble diagram (bin-size $\Delta z = 0.01$). *Right:*: Binned residuals from the best fitting cosmology ($\Omega_m = 0.31, \Omega_\Lambda = 0.69$).

## 2 Analysis procedure

For the Union compilation we have addressed a number of analysis issues that are relevant for any future compilation of SNe samples: 1) It is important that a sample of poorer quality will not degrade the impact of the higher quality data, such as the SNLS and ESSENCE high-redshift datasets which have recently been published. We achieve this by adjusting the weight of SNe belonging to a sample to reflect the dispersion we determine for the sample. With our prescription, SN samples with significant unaccounted-for statistical or systematic uncertainties are effectively deweighted. 2) The different supernova datasets are analyzed with the same analysis procedure. All SN lightcurves are fitted consistently in the observer frame system using SALT[18]. Where possible, the original band pass functions are used. 3) A reproducible, well-characterized and robust approach to selecting the good SNe Ia, and rejecting the questionable and outlier SNe, is used. 4) Finally, we applied a blindness procedure when developing the selection cuts and fit procedures used in the analysis. This ensures that our results are not (unconsciously) biased by our expectation.

We apply an empirical width-luminosity and color-luminosity correction to the SN peak magnitude [4,11,18], where the correction coefficients are determined during the cosmological fit procedure. Figure 1 shows the resulting Hubble-diagram of the 307 SNe that pass our selection cuts.

## 3 Systematic Uncertainties

The large sample of consistently analysed SNe allows to study potential systematic effects that could influence the cosmological analysis. We distinguish systematic errors that can be associated with a sample (e.g. due to observational effects) from those that are common to all the samples (e.g. due to astrophysical or fundamental calibration effects). The presence of systematic errors associated with specific samples could be uncovered by studying sampled averaged SN properties. Figure 2 (left) shows for each sample the mean deviation from the best fit Hubble-diagram. As can be seen, no significant deviation is observed. Another test for tension is the search for a slope in the Hubble diagram residual versus redshift distribution. This slope, which could e.g. uncover a Malmquist bias, is shown in Figure 3 (right) for the various samples. While not yet highly significant, it appears that the slope for some samples shows evidence for the presence of an systematic error (which is characterized and included in the final result [4]).

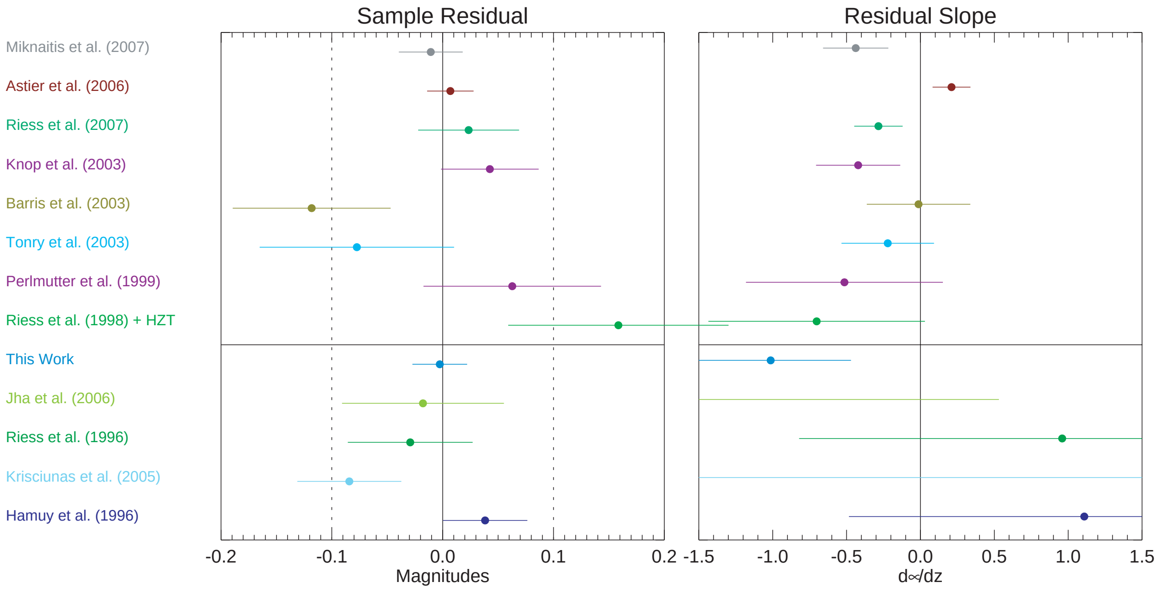

Figure 2: *Left:* The mean, sample averaged, deviation from the best fit model; *Right:* The slope of the Hubble-residual (in magnitudes) versus redshift, $d\mu_{\mathrm{residual}}/dz$. The parameters characterizing the different samples are used to uncover potential systematic problems.

The potential presence of SN-specific sources of systematic errors (e.g. evolution) have been tested by subdividing the sample. Dividing the sample into low-stretch and high-stretch SNe and performing independent fits, we found consistent cosmological parameters for the two samples. We have also studied the SN properties at low and high redshifts separately and did not observe significant differences in the populations.

All identified systematic uncertainties have been propagated into the final results by a slight extension of the conventional minimization schema[4]. One introduces a new distance modulus $\mu^{\mathrm{sys}} = \mu + \Delta M_i + \Delta M$, which is simply the usual distance modulus $\mu = 5\log(H_0 d_L(z))$ (here $d_L(z)$ is the luminosity distance and $H_0$ the Hubble constant) shifted by a sample dependent magnitude offset $\Delta M_i$ and a single sample independent magnitude offset $\Delta M$ added only for the higher redshift SNe ($z > 0.2$). The magnitude offsets $\Delta M_i$ reflect heterogeneity among the SNe samples while $\Delta M$ represents the common systematic error in the comparison of low vs high redshift SNe. Treating $\Delta M_i$ and $\Delta M$ as additional fit parameters, one defines $\chi^2_{\mathrm{sys}} = \chi^2 + \sum_i (\Delta M_i/\sigma_{M_i})^2 + (\Delta M/\sigma_M)^2$ to absorb the uncertainty in the nuisance parameters, $\sigma_{M_i}$ and $\sigma_M$, and obtain constraints on the desired physical fit parameters that include systematic errors. The results are shown for example in Figure 3 (top right panel).

## 4 Cosmological Results

With the Union SN compilation at hand, we can now proceed to the analysis of the cosmological parameters. The constraint we obtain from supernovae on the dark energy density is $\Omega_\Lambda = 0.713^{+0.027}_{-0.029}(\mathrm{stat})^{+0.036}_{-0.039}(\mathrm{sys})$, for a flat, $\Lambda$CDM Universe. Assuming a constant equation of state parameter, $w$, the combined constraints from SNe, WMAP-5 year CMB data[3] and SDSS BAO data[19] give $w = -0.969^{+0.059}_{-0.063}(\mathrm{stat})^{+0.063}_{-0.066}(\mathrm{sys})$. Figure 3 (left panel) shows the statistical constraints from the three different cosmological probes, along with their combination. The impact of including systematic errors is shown in the upper right panel, while the impact of adding the new sample of nearby SCP SNe is shown in the lower right panel. The results are consistent with $w = -1$, the value associated with a $\Lambda$CDM Universe. It is interesting to note that if one in addition fits for curvature, the constraints on $w$ will degrade only by 10%, and the

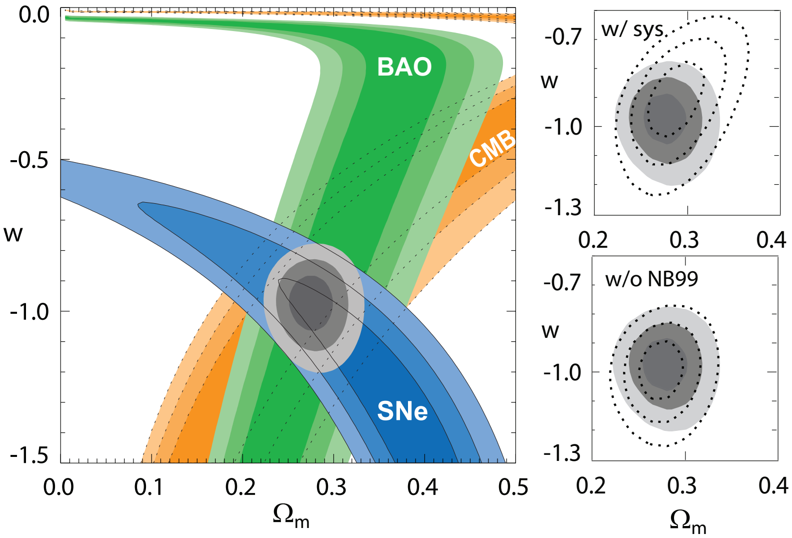

Figure 3: 68.3 %, 95.4 % and 99.7% confidence level contours on $w$ and $\Omega_M$, for a flat Universe. The left plot shows the individual constraints from CMB, BAO and the Union SN set, as well as the combined constraints (filled gray contours, statistical errors only). The upper right plot shows the effect of including systematic errors. The lower right plot illustrates the impact of the SCP Nearby 1999 data.

result, $\Omega_k = -0.010^{+0.010+0.006}_{-0.011-0.004}$, are consistent with a flat Universe. We obtain only relatively weak constraints on a $w$ that varies with redshift[4]. In particular, the current SN data do not yet significantly constrain $w$ at $z > 1$.

The SNe constraints from the Union set are the tightest to date, while at the same time we have encountered no limits to the potential use of current and future, high accuracy SN data as cosmological probes. We provide the Union SN data along with software for cosmological analysis through the web link "http://supernova.lbl.gov/Union".

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