Overview of Supernova Cosmology to Date

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Abstract

Type Ia supernovae provide simple, transparent tracers of the expansion history of the universe. They have been instrumental in breaking the matter dominated universe paradigm, demonstrating the current acceleration of the expansion, and probing back to the decelerating phase. We briefly review the progress to date and examine the promise that large numbers of supernovae with good systematics offer for uncovering the nature of dark matter.

A Simple, Direct Approach to the Cosmological Parameters

Type Ia supernovae (SNe Ia) provide straightforward cosmological measurement tools. Each is a strikingly similar explosion event whose physics can be analyzed in detail from its intensity and spectrum as it brightens and fades along its light curve. Most observed SNe Ia have nearly the same peak luminosity, and the variations that do exist can be correlated with other observables and hence calibrated to 5% in distance (0.1 magnitudes) (Hamuy et al., 1996; Riess, Press, & Kirshner, 1996) or equivalently lookback time for an individual supernova.

The wavelengths of the photons from the supernova are stretched—“redshifted”—in exact proportion to the expansion of the universe during the time the photon propagates to us. Thus the comparison of SN Ia redshifts and magnitudes provides a particularly simple measurement of the expansion history of the universe: the apparent magnitude indicates the distance and hence time back to the supernova explosion, while the redshift measures the total relative expansion of the universe since that time.

From such an expansion history we can determine the contributions of decelerating and accelerating energies – mass density Ω_M, vacuum energy density Ω_Λ, and/or other undetected “dark energies”.

This is an extremely transparent methodology. Aside from the basic cosmological equations, there is no astrophysical model dependence in this empirically based method. Together with numerous cross checks available from detailed spectral information, this simplicity makes this approach well determined and robust.

The Current Results: Questions Answered and Posed by an Accelerating Universe

The cosmological results from the magnitude-redshift measurements of a few score SNe Ia already break the matter dominated universe paradigm (Perlmutter et al., 1999; Riess et al., 1998) as seen in Fig. 1. Most striking is the indication (at 95% confidence from supernovae alone) that we live in an accelerating universe, which must be dominated by a positive cosmological constant or other exotic dark energy whose pressure is negative and large.

For measurements over a modest range in redshift z the magnitude or luminosity distance is nearly degenerate for various combinations of (Ω_M,Ω_Λ). However, this degeneracy can be broken if the data extend far enough in redshift (Goobar & Perlmutter, 1995). Using this approach, two independent research groups have presented compelling observational evidence for an accelerating universe: the Supernova Cosmology Project (SCP) (Perlmutter et al., 1997, 1998, 1999) begun in 1989, and the High-Z Supernova Search Team (HIZST) (Schmidt et al., 1998; Garnavich et al., 1998; Riess et al., 1998) which found their first distant supernova in 1995.

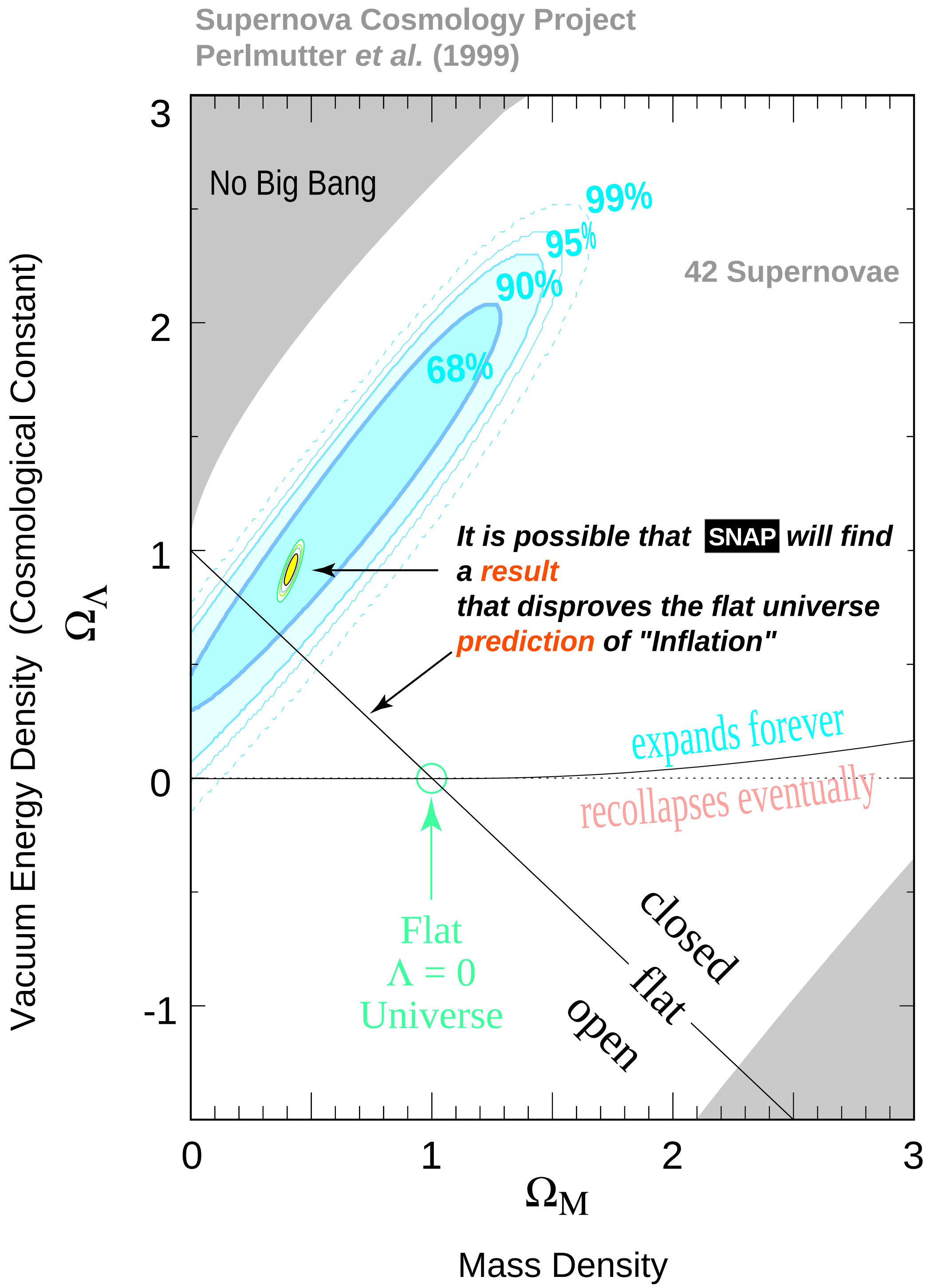
The basic procedure consists of *a)* discovering large numbers of high–z SNe Ia (> 20 per observing run) while they are still on the rise, *b)* obtaining spectroscopic follow-up within a few days of discovery to confirm the SN type and redshift, *c)* acquiring ground-based and HST light curve photometry, and *d)* analyzing the data to obtain peak magnitudes and measure Ω_M and Ω_Λ.

Figure 2 shows how the correlation between light curve shape and peak magnitude reduces the scatter for use in distance determination. Use of multiple spectral passbands allows separation of intrinsic brightness variations from extraneous effects due to dust absorption and spectral filter corrections.

In parallel the two teams have discovered ~ 100 SNe Ia at $z > 0.3$, with spectral confirmation. With each successive search run they have tailored the filters and exposure times to search at progressively larger distances, reaching the point now of starting to build a statistically significant sample of $1 < z < 1.25$ supernovae.

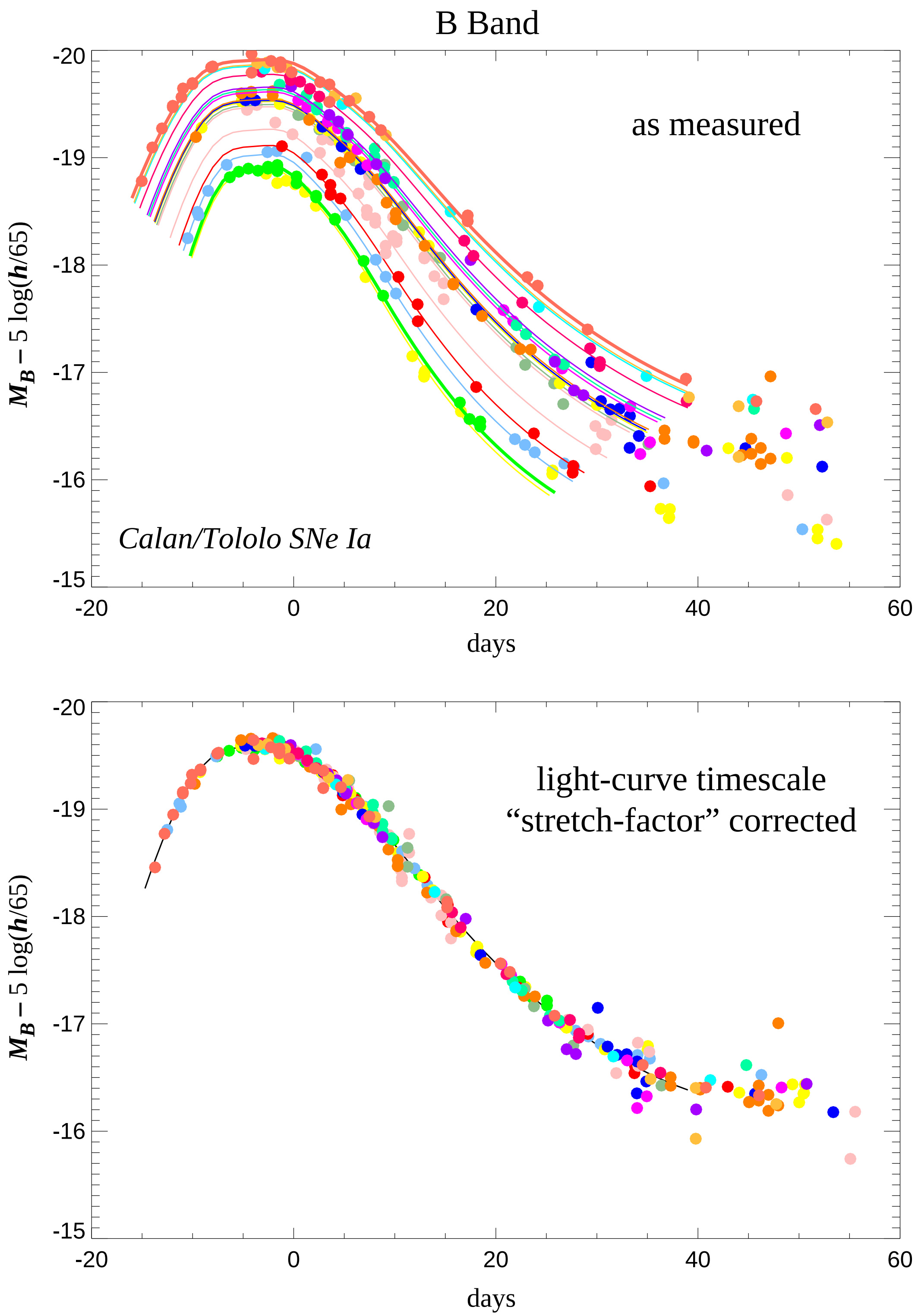
Figure 3 shows a Hubble diagram based on results obtained by the SCP for 42 SNe with $0.18 < z < 0.83$. It indicates that we live in a low mass-density universe, and presents strong evidence for a cosmological constant [Perlmutter et al. (1999); see also Riess et al. (1998)]; the best fit is $\Omega_M = 0.28 \pm 0.08$ for a flat universe, and limits the combination $0.8\,\Omega_M - 0.6\,\Omega_\Lambda$ to -0.2 ± 0.1. Similar results were obtained by HIZST.

Figure 4 shows constraints on dark energy models, parametrizing the field's



It is possible that* SNAP *will find a result that disproves the flat universe prediction of "Inflation"

Figure 1: 68%, 90%, and 99% confidence regions in the Ω_M—Ω_Λ plane from the 42 distant SNe Ia in Perlmutter et al. (1999). These results rule out a flat, matter dominated $[\Omega_M = 1,\ \Omega_\Lambda = 0]$ cosmology and provide strong evidence (probability $> 99\%$) for $\Omega_\Lambda > 0$. Also shown is the expected confidence region from the SNAP satellite; it can test the flat universe prediction of inflation.



Kim, *et al.* (1997)

Figure 2: The relationship between light curve width and the luminosity of a SN Ia is seen in these two panels. The top panel shows several SNe Ia from the Calán/Tololo Supernova Survey arranged by their observed relative luminosity (all objects were in the Hubble Flow). The bottom graph shows how "stretch" can be used to describe the light curves with one parameter.

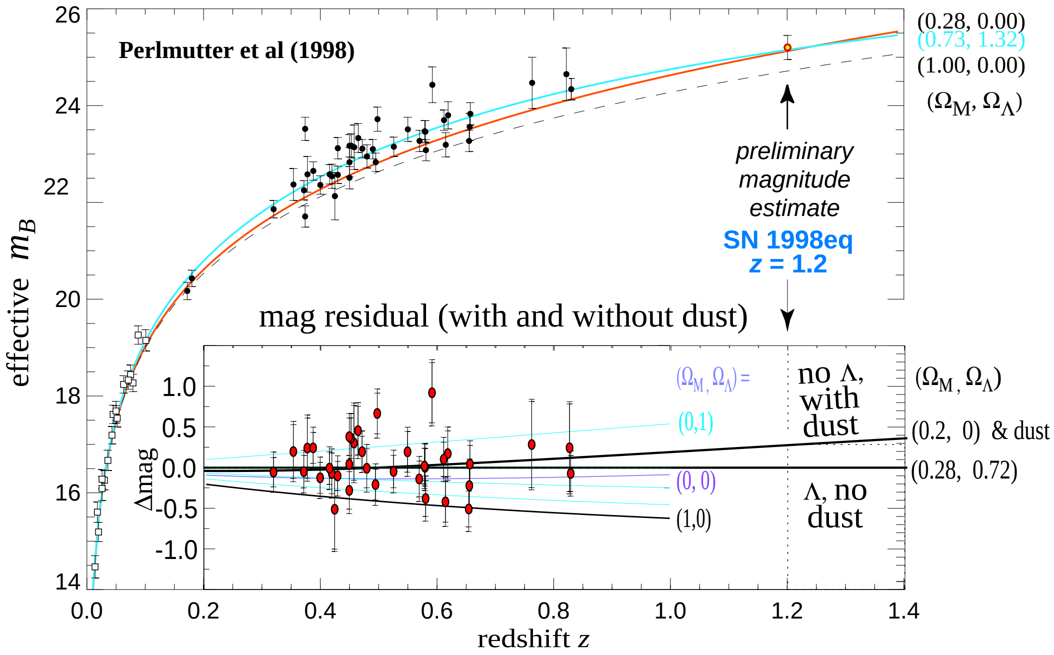


Figure 3: Hubble diagram for 42 high-z SNe (Perlmutter et al., 1999). The best-fit world model with $(\Omega_M, \Omega_\Lambda)$ = (0.73, 1.32) is drawn through the data (solid line). The Einstein-de Sitter case (1.0, 0.0) is strongly excluded by the current data (dashed line). The case $(\Omega_M, \Omega_\Lambda) = (0.28, 0.00)$ indicates that some contribution from the cosmological constant is required for values of Ω_M favored by dynamical measurements. The magnitude difference between the best-fit world model and suitable ones with Ω_Λ=0 show redshift dependencies which would be very hard to mimic within the context of SNe evolution or gray dust hypotheses (see inset panel). By extending our survey beyond z=1, the *form* of the Hubble diagram alone would become sufficient evidence to support a cosmological constant. The preliminary magnitude estimate of our highest redshift SN1999eq at z = 1.2 is suggestive, but more analysis and more SNe at this redshift are necessary.

equation of state ratio as $w = p/\rho$. Cosmic strings ($w = -1/3$) are already strongly disfavored. Figure 5 illustrates possible future limits from a space telescope optimized for supernova detection, SNAP.

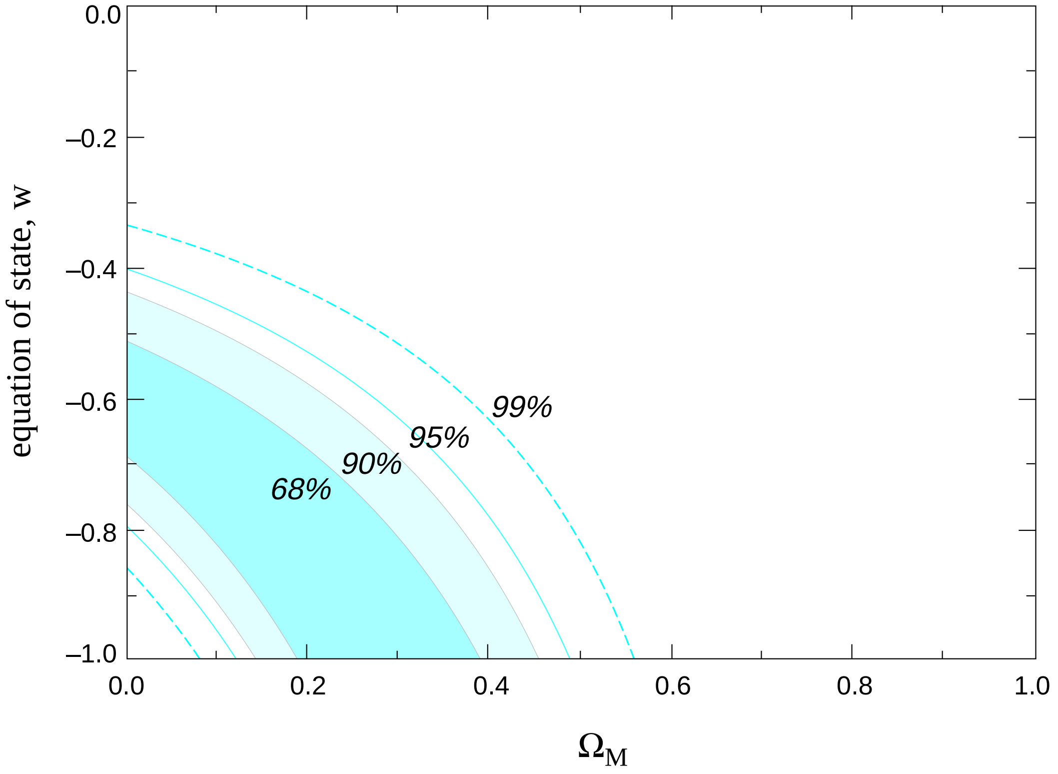


Figure 4: Best-fit 68%, 90%, 95%, and 99% confidence regions in the $\Omega_{\rm M}$–w plane for an additional energy density component, Ω_w, characterized by an equation-of-state ratio $w = p/\rho$. (If this energy density component is Einstein's cosmological constant, Λ, then the equation of state is $w = p_\Lambda/\rho_\Lambda = -1$.) The fit shown is for a flat cosmology ($\Omega_{\rm M} + \Omega_w = 1$).

These current results raise important questions: what is the nature of the dark energy; what is the value of its energy density and of the matter density which determine the curvature of the universe; is the fate of the universe never ending accelerated expansion – a new and final inflationary epoch? For answers we require a deeper survey with tightly controlled statistical and systematic uncertainties.

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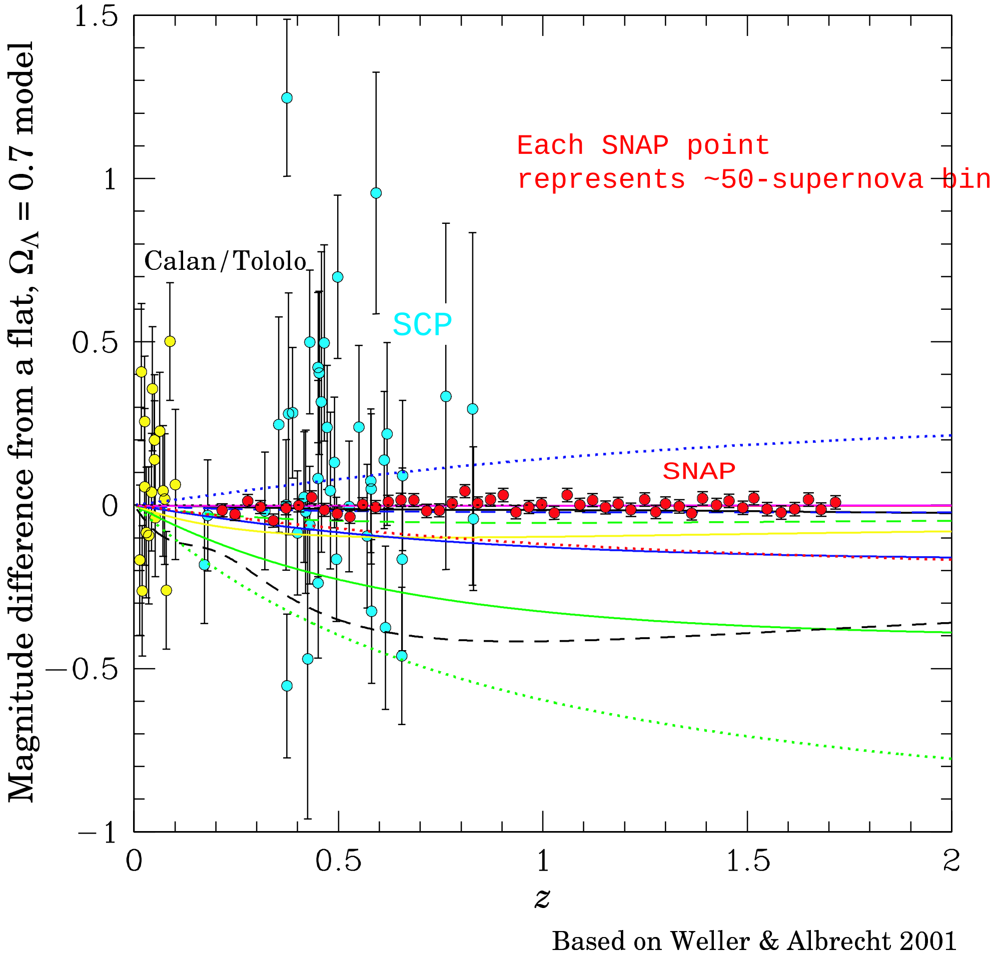

Figure 5: SNAP constraints on dark energy models, viewed in the magnitude-redshift plane. The current set of 18+42 supernovae is supplemented by a set of simulated SNAP supernovae (each SNAP point represents 50 supernovae). Theoretical curves correspond to a variety of dark energy models currently found in the literature. The plot is adapted from Weller & Albrecht (2001).

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