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Is cosmic acceleration slowing down?

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We investigate the course of cosmic expansion in its *recent past* using the Constitution SN Ia sample, along with baryon acoustic oscillations (BAO) and cosmic microwave background (CMB) data. Allowing the equation of state of dark energy (DE) to vary, we find that a coasting model of the universe ($q_0 = 0$) fits the data about as well as Lambda cold dark matter. This effect, which is most clearly seen using the recently introduced Om diagnostic, corresponds to an increase of Om and q at redshifts $z \lesssim 0.3$. This suggests that cosmic acceleration may have already peaked and that we are currently witnessing its slowing down. The case for evolving DE strengthens if a subsample of the Constitution set consisting of SNLS + ESSENCE + CfA SN Ia data is analyzed in combination with BAO + CMB data. The effect we observe could correspond to DE decaying into dark matter (or something else).

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The existence of cosmic acceleration at redshifts less than ~0.5 appears to be well established by several independent data sets including: SN Ia luminosity distances, cosmic microwave background temperature anisotropy and polarization maps, and baryon acoustic oscillations in the galaxy power spectrum. Most recent analysis performed using the data mentioned above [1], as well as data from Chandra [2], Sloan Digital Sky Survey (SDSS) [3] and cluster catalogues, show that if the dark energy (DE) equation of state (EOS) $w \equiv p_{\rm DE}/\rho_{\rm DE}$ is assumed to be a constant, then there remains little room for departure of DE from the cosmological constant, since $|1 + w| < 0.06$ at the 1σ confidence level (C.L.). However, in the absence of compelling theoretical models with an unevolving EOS, one must reexamine the data impartially by removing this prior, if one is to look for serious alternatives to the cosmological constant [4].

In this paper, we drop the assumption of $w = \text{const}$ when analyzing data from the Constitution supernovae data set [5], together with BAO data at $z = 0.2$ and $z = 0.35$ [6] and the observed cosmic microwave background (CMB) shift parameter R. The data are analyzed using the popular Chevalier-Polarski-Linder (CPL) ansatz [7] together with the recently introduced $Om(z)$ diagnostic [8]:

$$Om(z) \equiv \frac{h^2(z) - 1}{(1+z)^3 - 1}, \tag{1}$$

where

$$h^2 = \frac{H^2(z)}{H_0^2} = \Omega_{0m}(1+z)^3 + \Omega_{\rm DE},$$
$$\Omega_{\rm DE} = (1 - \Omega_{0m}) \exp\left\{3\int_0^z \frac{1 + w(z')}{1 + z'} dz'\right\} \tag{2}$$

is the expansion history of a spatially flat Friedmann-Robertson-Walker (FRW) Universe with scale factor $a(t)$ and Hubble parameter $H(z) \equiv \dot{a}/a$. The CPL ansatz expresses the EOS in terms of the redshift z in the following form [7]:

$$w(z) = w_0 + w_1 \frac{z}{1+z}. \tag{3}$$

In contrast to $w(z)$ and the deceleration parameter $q(z) \equiv -\ddot{a}/aH^2$, the $Om(z)$ diagnostic depends upon no higher derivative of the luminosity distance than the first one. Om is also distinguished by the fact that $Om(z) = \Omega_{0m}$ for Lambda cold dark matter (ΛCDM). Om is very useful in establishing the properties of DE. For an unevolving EOS: $1 + w \simeq [Om(z) - \Omega_{0m}](1 - \Omega_{0m})^{-1}$ at $z \ll 1$, consequently a larger $Om(z)$ is indicative of a larger w; while at high z, $Om(z) \to \Omega_{0m}$, as shown in Fig. 1.

The present analysis uses the recently compiled "Constitution set" [5] of 397 type Ia supernovae covering a redshift range from $z_{\min} = 0.015$ to $z_{\max} = 1.551$. The Constitution set is the largest SN Ia luminosity distance sample currently available and includes 139 SN Ia at $z < 0.08$. Our analysis considers the SN Ia data individually as well as in combination with BAO distance measurements obtained at $z = 0.2$ and $z = 0.35$ from the joint analysis of the 2dF Galaxy Redshift Survey and SDSS data [6]. The BAO distance ratio $D_V(z = 0.35)/D_V(z = 0.20) = 1.736 \pm 0.065$ was shown in [6] to be a relatively model independent quantity. Here $D_V(z)$ is defined as

$$D_V(z_{\rm BAO}) = \left[\frac{z_{\rm BAO}}{H(z_{\rm BAO})}\left(\int_0^{z_{\rm BAO}} \frac{dz}{H(z)}\right)^2\right]^{1/3}. \tag{4}$$

We also use the CMB shift parameter [1] which is the reduced distance to the last scattering surface ($z_{\rm ls} = 1090$)

$$R = \sqrt{\Omega_{0m}} \int_0^{z_{\rm ls}} \frac{dz}{h(z)} = 1.71 \pm 0.019. \tag{5}$$

While SN Ia and BAO data contain information about the Universe at relatively low redshifts, the R parameter probes the entire expansion history up to last scattering at

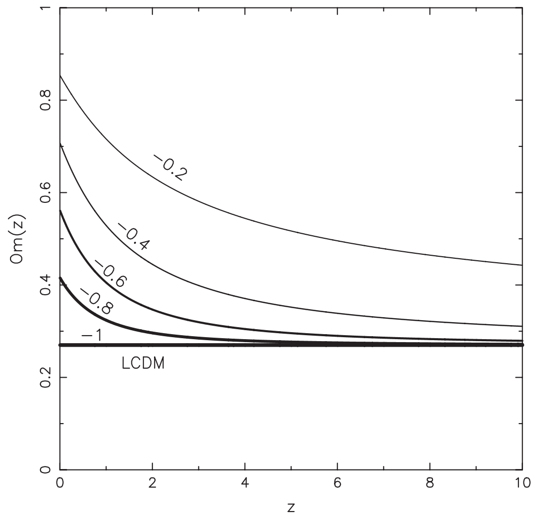

FIG. 1. The Om diagnostic is shown as a function of redshift for DE models with $\Omega_{0m} = 0.27$ and $w = -1, -0.8, -0.6, -0.4, -0.2$ (bottom to top). For Phantom models (not shown) Om would have the opposite curvature.

$z_{\rm ls}$. Because of this, our analysis also examines the goodness of fit for CPL parametrization when applied simultaneously to data at low and high redshifts.

Figure 2 shows $q(z)$ and $Om(z)$ reconstructed using (3) and SN Ia + BAO data (upper panels) and SN Ia + BAO + CMB data (lower panels). It is interesting that the best fit flat ΛCDM model ($\Omega_{0m} = 0.287$) satisfying SN Ia + BAO data does not lie within the 1σ C.L. of our best reconstruction. By contrast, [5] obtain $1 + w = 0.013^{+0.066}_{-0.068}$ after assuming $w =$ const, which underscores the difference made by dropping the $w =$ cons constraint. It is interesting to mention that the reduced χ^2 also drops from $\chi^2_{\rm red} = 1.182$ in the case of the ΛCDM model to $\chi^2_{\rm red} = 1.171$ in the case of the varying dark energy model which makes the assumption of the additional parameter worthwhile.

The growth in the value of $Om(z)$ at low z in the upper panel of Fig. 2 is striking, and appears to favor a DE model with an EOS which increases at late times [compare with the $Om(z)$ for a constant EOS in Fig. 1]. This could be preliminary evidence for a decaying DE model since, in this case, the EOS would increase at late times, resulting in an increase in the low z value of the Hubble parameter and therefore also of $Om(z)$.

These results change dramatically with the inclusion of CMB data. The lower panel of Fig. 2 shows that our reconstruction of $Om(z)$ is now perfectly consistent with ΛCDM—for which $Om(z)$ is unevolving. What one observes here is an incompatibility of the CPL parametriza-

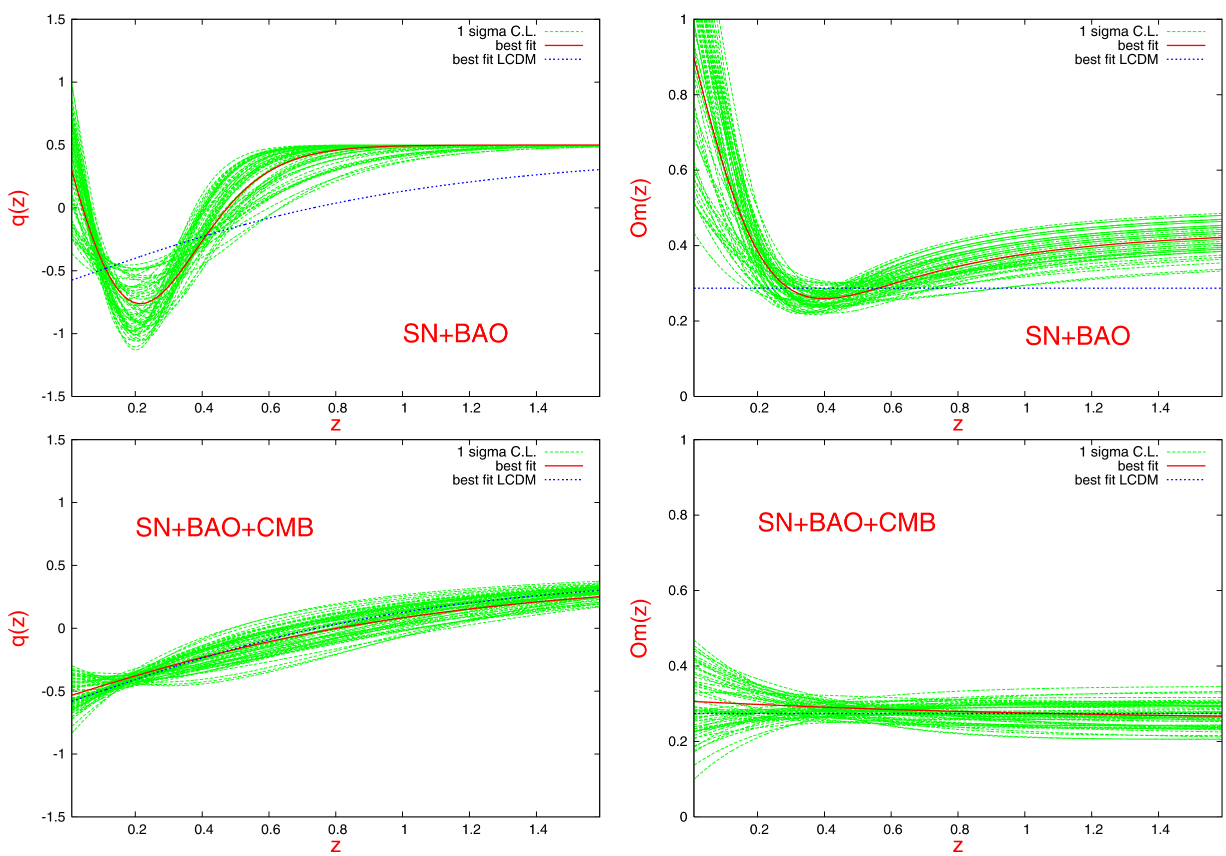

FIG. 2 (color online). Reconstructed $q(z)$ and $Om(z)$ from SN Ia + BAO data (upper panels) and SN Ia + BAO + CMB data (lower panels) using the CPL ansatz. Solid red lines show the best fit values of $Om(z)$ and $q(z)$ while dashed green lines show the 1σ C.L. Dotted blue lines represent the best fit spatially flat ΛCDM model. The dramatic difference between the upper panels and the lower ones is indicative of the inability of the CPL parametrization to fit the data at low and high redshifts simultaneously.

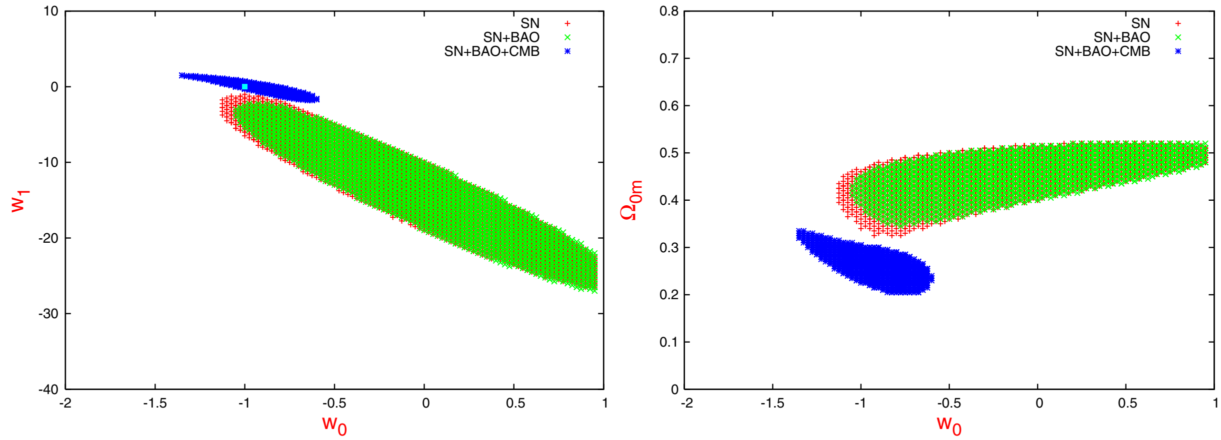

FIG. 3 (color online). 1σ contours for CPL parameters w_0-w_1 (left panel) and w_0-Ω_{0m} (right panel) reconstructed using SN Ia data (red plusses), SN Ia + BAO data (green crosses) and SN Ia + BAO + CMB data (blue stars). Light blue dot at $w_0 = -1$, $w_1 = 0$ in the left panel represent spatially flat ΛCDM model. Note the consistency between SN Ia and BAO data. The absence of any overlap between the 1σ contours for SN Ia + BAO + CMB and SN Ia + BAO data could be indicative of tension between the CPL parametrization and the data. We should note here that plotting small contours that indicate tight constraints on the parameters is misleading when the best fit result produces a bad fit to the data (blue contours).

tion for $w(z)$ with this combination of data sets. In other words, the functional form of the CPL ansatz is unable to fit the data simultaneously at low and high redshifts. This can be clearly seen if we compare $\chi^2_{\rm SN+BAO} = 461.63$ ($\chi^2_{\rm red} = 1.171$), with the significantly larger $\chi^2_{\rm SN+BAO+CMB} = 467.07$ ($\chi^2_{\rm red} = 1.182$). The addition of one more data point (the CMB shift parameter) increases the best fit χ^2 by more than 5. Support for this viewpoint is also provided by Fig. 3, which shows the best fit regions in parameter space obtained using the CPL ansatz after fitting to SN Ia (red plusses), SN Ia + BAO (green crosses) and SN Ia + BAO + CMB (blue stars) data. Contrast the good overlap between best fit regions obtained using SN Ia and SN Ia + BAO data, with the relative isolation of the best fit region obtained using SN Ia + BAO + CMB data.

Our reconstruction of $Om(z)$ appears to favor DE with an increasing EOS at low redshifts $z \lesssim 0.3$ (Fig. 2 upper-right panel). We have also seen that the CPL ansatz is strained to describe the DE behavior suggested by data at low and high z. We believe the reason for this stems from the fact that the CPL ansatz implicitly assumes that the redshift interval from $z = 0$ to $z \sim 2$ represents nothing special for DE, so that $w(z)$ can safely be expanded in a Taylor series in powers of $z/(1 + z)$ in this interval. This need not, however, be true, since models have been suggested in which dark energy decays with a characteristic time of order of the present age of the Universe [4,9]. Note also that the large negative value of w_1 (Fig. 3) suggests that DE was practically nonexistent at high redshifts. This too could be an ansatz-related feature, since the reliability of (3) at high redshifts remains somewhat ambiguous. Keeping these issues in mind, we reanalyze the data using a simple toy model for $w(z)$ which encapsulates the main features of the effect discovered, and show that this ansatz

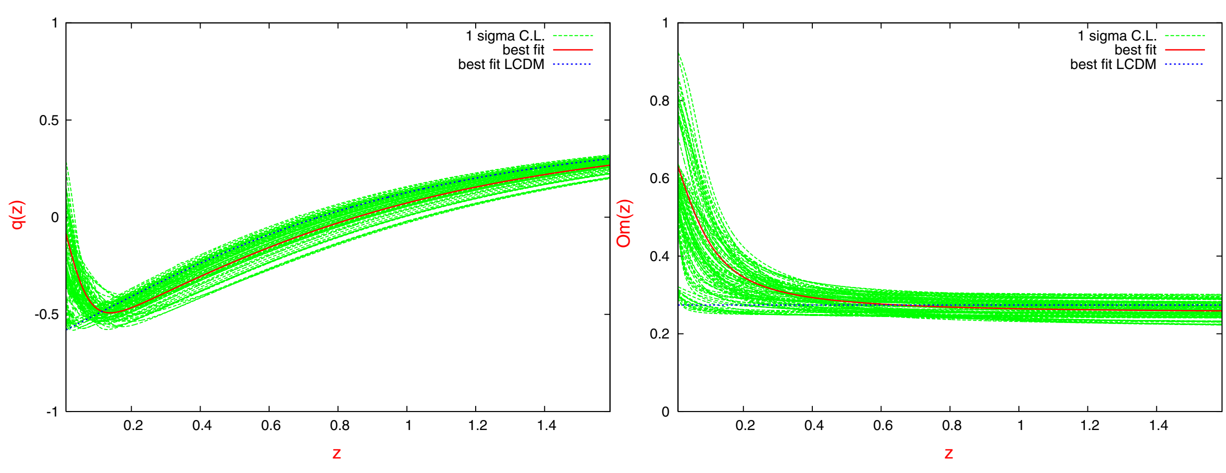

FIG. 4 (color online). The cosmological deceleration parameter $q(z)$ (left panel) and $Om(z)$ (right panel) reconstructed using a combination of SN Ia, BAO and CMB data and the ansatz (6). Solid red lines show best fit reconstructed results while dashed green lines show reconstructed results within 1σ C.L. Dotted blue lines show the best fit spatially flat ΛCDM model.

can provide a better fit to the combination of SN + BAO + CMB data than CPL.

Our ansatz is

$$w(z) = -\frac{1 + \tanh[(z - z_t)\Delta]}{2} \quad (6)$$

(a similar form was used in [10] and other papers to search for fast phase transitions in DE at larger values of z). This fit ensures $w = -1$ at early times, and then increases the EOS to a maximum of $w \sim 0$ at low z. It has the same number of free parameters as the CPL ansatz but does not permit the crossing of the phantom divide at $w = -1$. The best fit cosmology obtained using this ansatz has $z_t = 0.008$ (i.e. $z_t \approx 0$), $\Delta = 12.8$, $\Omega_{0m} = 0.255$ and $\chi^2_{\mathrm{SN+BAO+CMB}} = 466.50$, and presents an improvement ($\Delta\chi^2 = -0.6$) over the best fit for the same data set obtained using the CPL ansatz. Figure 4 shows the deceleration parameter q and the Om diagnostic reconstructed using (2) and (6). Interestingly, ΛCDM as well as a universe which is currently coasting ($q_0 \simeq 0$), can both be accommodated by the data at roughly the same level of confidence!

To check the robustness of our results we redo our analysis on a subsample of the Constitution data set, namely the SNLS + ESSENCE + CfA SN Ia data (234 data points in all). Our results, shown in Fig. 5 for the CPL ansatz, are summarized below:

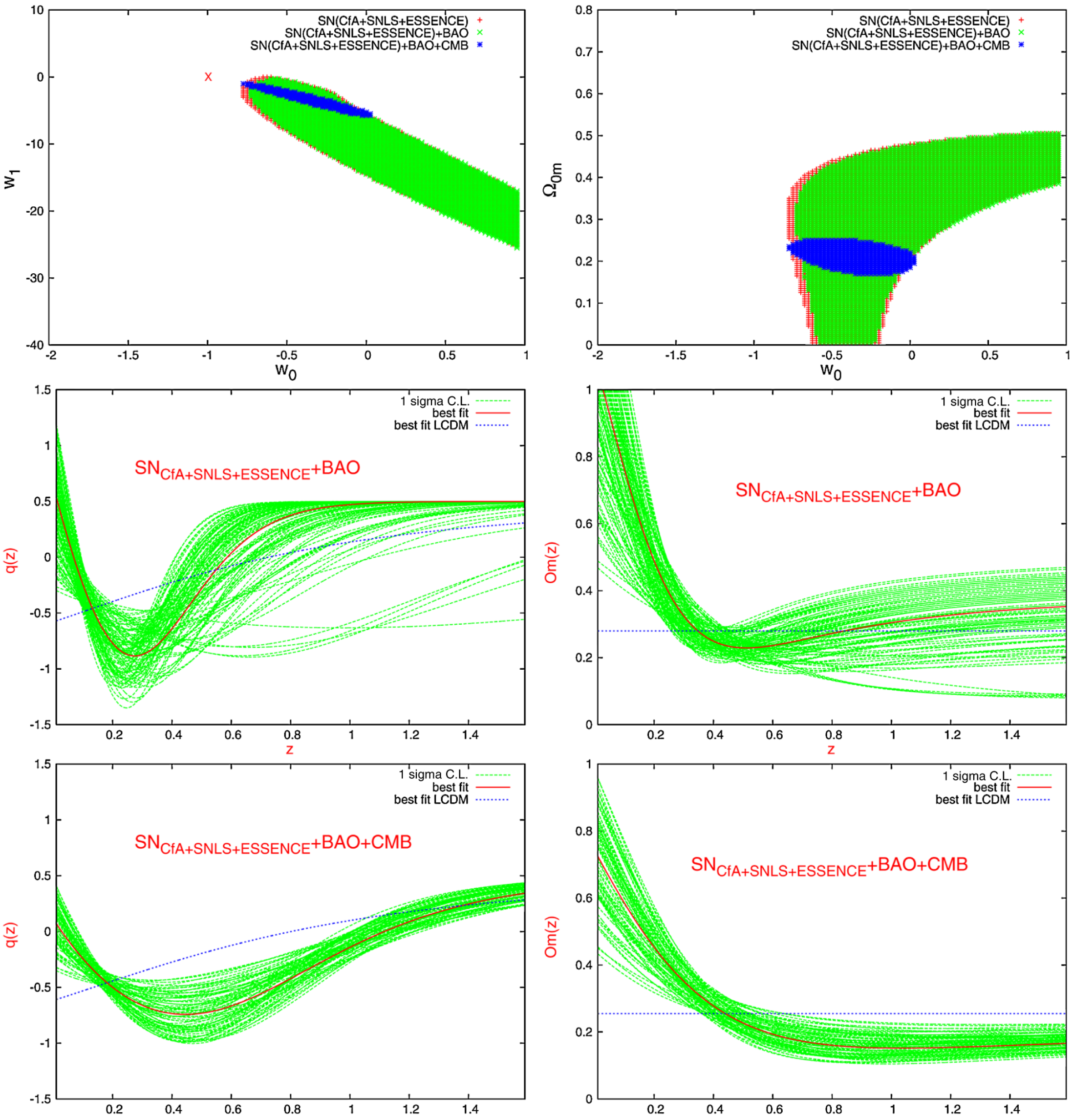

FIG. 5 (color online). Top: 1σ contours for CPL parameters w_0-w_1 (left panel) and w_0-Ω_{0m} (right panel) reconstructed using SN Ia data (SNLS + ESSENCE + CfA, red plusses), SN Ia + BAO data (green crosses) and SN Ia + BAO + CMB data (blue stars). Note the compatibility between the different data sets and that spatially flat ΛCDM (red cross at $w_0 = -1$, $w_1 = 0$ in the left panel) appears to be in tension with this combination of data. Middle and bottom: Reconstructed $q(z)$ and $Om(z)$ from SN Ia + BAO data (middle). Reconstructed $q(z)$ and $Om(z)$ from SN Ia + BAO + CMB data (bottom). In the middle and bottom panels solid red lines show the best fit values of $Om(z)$ and $q(z)$ while dashed green lines show the 1σ C.L. Dotted blue lines represent the best fit spatially flat ΛCDM model.

(1) An excellent overlap exists between the 1σ contours w_0-w_1 (top left) and w_0-Ω_{0m} (top right) reconstructed using SN Ia, SN Ia + BAO and SN Ia + BAO + CMB data. This demonstrates that the CPL ansatz works quite well for this combination of data sets and hints that the tension noticed in Fig. 3 could be coming from data sets which have been excluded from the present SN Ia compilation: namely the Gold data, the high z Hubble Space Telescope data and older SN Ia data sets. The visual impression conveyed by this panel, which appears to support evolving DE, receives statistical support: the best fit χ^2 for SN Ia data is 267.69, while $\chi^2 = 267.92$ for SN Ia + BAO and $\chi^2 = 268.89$ for SN Ia + BAO + CMB. We therefore find that the χ^2 values for the three data sets (SN Ia, SN Ia + BAO, SN Ia + BAO + CMB) lie much closer together for the data shown in Fig. 5, compared to the data in Fig. 3.

(2) A larger value of $Om(z)$ and $q(z)$ at low redshifts is supported by the present analysis of SNLS + ESSENCE + CfA supernovae in combination with BAO and CMB data (Fig. 5 middle and bottom). Indeed, coasting cosmology ($q_0 \simeq 0$) provides an excellent fit to the data.

(3) The fact that the spatially flat ΛCDM shows weaker consistency with the SN Ia subsample + BAO + CMB data is clearly seen from the best fit values for ΛCDM: (i) $\chi^2 = 274.64$ using only SN Ia ($\Omega_m = 0.28$), (ii) $\chi^2 = 275.87$ for SN Ia + BAO ($\Omega_m = 0.28$), (iii) $\chi^2 = 276.84$ for SN Ia + BAO + CMB ($\Omega_m = 0.26$). Comparing with the results for evolving DE discussed earlier, we find that the incremental value of $\Delta\chi^2$ between the best fit evolving DE model and best fit ΛCDM is $\simeq 8$, and favors evolving DE (the reduced χ^2 drops from $\chi^2_{\rm red} = 1.188$ in the case of ΛCDM model to $\chi^2_{\rm red} = 1.159$ in the case of varying dark energy model).

To summarize, the recently released Constitution SN Ia data set appears to support DE evolution at low redshifts. There also appears to be some tension between low z (Constitution SN Ia + BAO) and high z (CMB) data, when analyzed using the CPL ansatz. (However, this tension decreases when only a subsample of the Constitution set is analyzed.) There could be several reasons for this.

(i) Systematics in some of the data sets is not sufficiently well understood. This effect may have a purely astronomical explanation and be a result of some systematic effect, e.g. if new nearby CfA SN Ia are brighter on average. However, we have additionally found that if the effect is assumed to be cosmological, then the implied DE behavior at low redshifts (using SN Ia data) is more consistent with a rather large value of the $D_V(z = 0.35)/D_V(z = 0.20)$ BAO distance ratio derived in [6].

(ii) Another possibility is that this behavior of Om, w, q is an *apparent* one, which is induced by a local spatial inhomogeneity—a kind of a "Hubble bubble," but with a large-scale matter overdensity.

(iii) Different SN Ia subsamples comprising the Constitution set have varying properties.

(iv) The CPL ansatz is not versatile enough to accommodate the cosmological evolution of dark energy suggested by the data.

Clearly one must wait for more data before deciding between these alternatives. Note that the bulwark of support for evolving DE comes from BAO data in conjunction with Constitution SN Ia data [5] which includes 139 SN Ia at $z < 0.08$. As concerns ΛCDM, our conclusion is that it is still viable at the 95% confidence level but perhaps one should take its subtle challenges more seriously [11].

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