Alleviating ΛCDM tension in Pantheon in late time quantum cosmology

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Surveys of the Local Universe show a Hubble expansion significantly greater than ΛCDM estimates from the Cosmic Microwave Background by Planck. This may present a challenge to our application of general relativity to cosmology. Such tensions are expected in quantum cosmology, wherein de Sitter space is unstable by dark energy from the cosmological horizon $\mathcal{H}$. We report on a novel probe of late time cosmology in terms of matter density ω_m estimated over inner intervals $[0, z_{\max}]$. Independent of Planck, Pantheon data over $0 < z_{\max} \leq 2.26$ are found to exclude ΛCDM by 4.3σ. In quantum cosmology, this reduces to 2.5σ.

Hubble parameter | dark energy | quantum gravity

Gravitation remains the most mysterious force in Nature, governing the large scale evolution and structure formation of the Universe down to the scale of galaxies and solar systems. While the theory of general relativity enjoys tremendous success (30) extending Newton's theory of gravitation to black holes and their violent interactions (1), its applications to cosmology is not without the need for dark energy and dark matter far more than what is present in ordinary baryonic matter (3, 19, 20). Perhaps, then, we are missing something in a self-consistent application of general relativity to the Universe on the largest scales. Unique to our essentially three-flat homogeneous and isotropic universe is the presence of a cosmological horizon $\mathcal{H}$ (e.g 11). It marks the absence of null-infinity $\mathcal{N}$ in asymptotically flat Minkowski spacetime, otherwise conveniently assumed in applications to, say, a solar system.

Assuming a constant dark energy density, the frame-work of ΛCDM is exceptionally effective in modeling temperature fluctuations in the Cosmic Microwave Background (CMB) across a broad range in angular scales (3). At present resolution, this leaves few residuals that stand out *except* for the Hubble parameter H_0 in confrontation with completely independent measurements of the expansion of the Universe in surveys of the Local Universe (19, 20). From the perspective of gravitation, H_0 deserves special attention in facing $\mathcal{H}$, that otherwise might be ignored at the smaller angular scales probed by Planck.

Our applications of general relativity are based on a Hilbert action S in terms of the Lagrangian of classical general relativity (e.g. 29). It forms a starting point for quantization by Feynman's path integral formulation, previously considered in pioneering studies of spatially closed early cosmologies (15). In this approach, S quite generally turns into a total phase upon setting Planck's constant $\hbar = 1$. In astrophysical applications, S becomes meaningful as a phase difference $S - S_0$, where S_0 represents well-defined large distance behavior. For gravitational interactions on the scale of a solar system, S_0 is a constant that may be put to zero inferred from a Lorentz invariant $\mathcal{N}$.

In our Universe, however, large distance behavior is set by the cosmological horizon $\mathcal{H}$ instead of $\mathcal{N}$. $\mathcal{H}$ is defined in the geometric optics limit as an apparent horizon surface at Hubble radius $R_H = c/H$ in a three-flat Friedman-Robertson-Walker line-element of a homogeneous and isotropic universe, where c is the velocity of light. Now, S_0 represents a covariant contribution from $\mathcal{H}$. In an evolving Universe, $\mathcal{H}$ is dynamic, implying S_0 is dynamic as well, the result of which may be expressed by a suitable addition to aforementioned Lagrangian of general relativity shown below.

To probe late time cosmology for anomalies beyond ΛCDM independet of Planck, we here explore a novel probe of matter density ω_m estimated over running inner intervals $[0, z_{\max}]$. In essence, ω_m parameterises curvature in the graph $(z, H(z))$, that will be sensitive to the nature of dark energy - dynamic in quantum cosmology or static in ΛCDM. It entirely conceivable that the first renders the future of ΛCDM - de Sitter space with vanishing matter content - non-existent on a Hubble time scale (2, 5, 6, 9, 18, 25, 26). If so, ΛCDM does not hold true to all orders today and tensions in cosmological parameter estimation from model-independent surveys of the Local Universe versus ΛCDM analysis of the CMB are expected.

The expansion history of the Local Universe therefore promises signatures of fundamental physics of gravitation beyond ΛCDM (e.g. 14, 24) that may be probed by high resolution supernova surveys using running redshift intervals (e.g. 13, 21). We here elaborate on this prospect using the recent Pantheon sample (Fig. 1) (22) in light of ΛCDM data from Planck (3).

Dark energy driving late time cosmological expansion. Evolution at late time (small z) is effectively parameterized by the present values of the Hubble parameter H_0 and matter density $\omega_m = \Omega_{m,0}$. In geometrical units ($c = 1$ and Newton's

Significance Statement

Cosmological expansion appears significantly faster in surveys of the Local Universe than in Planck analysis of the Cosmic Microwave Background (CMB). Supernova surveys such as Pantheon promise to provide novel probes of the dark energy driving this late time cosmological evolution. In quantum cosmology by the path integral formulation, dark energy derives from the cosmological horizon that renders de Sitter space unstable. ΛCDM hereby cannot hold true to all orders today. We report on significant tensions arising from fits to ΛCDM and their reduction in fits to late time quantum cosmology.

The first author designed the present study and wrote the manuscript.

There are no conflicts of interest.

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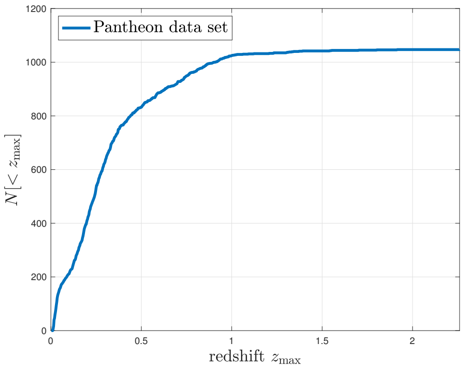

Fig. 1. By counts $N[< z_{\max}]$, the 1048 supernovae in the Pantheon data set densely cover low redshifts, e.g., $N[< 0.145] = 280$.

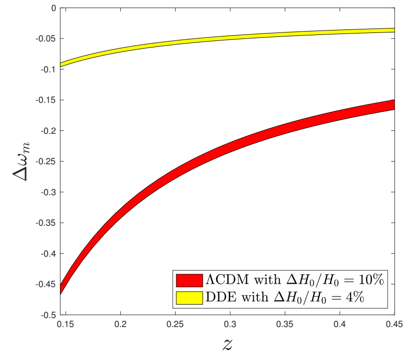

Fig. 2. In two-parameter fits (H_0, ω_m) to data, tensions in H_0 and ω_m are correlated by Eq. (6). Shown is $\Delta\omega_m$ in response to a perturbation ΔH_0 as a function of redshift z. Sensitivity diverges at small z for the cosmological models at hand, here shown for a fiducial deviations of $\Delta H_0/H_0 = 10\%$ and, respectively, 4%. The width of the curves refers to a canonical range of $0.26 < \omega_m < 0.34$.

constant $G = 1$), the cosmological vacuum has a dark energy density $\rho_\Lambda = \Lambda/8\pi$. Including ρ_Λ in the Hamiltonian energy constraint of the Einstein equations gives

$$H(z) = H_0 h(z, \omega_m) \quad [1]$$

with

$$h(z) = \sqrt{1 - \omega_m + \omega_m (1+z)^3} \quad [2]$$

when Λ is constant - ΛCDM with unknown origin of Λ.

For a consistent application of general relativity to cosmology, we here consider aforementioned phase reference S_0 from large distance behavior in three-flat cosmologies - Mach's principle in quantum cosmology by the path integral formulation. In contemporary language, the cosmological vacuum is said to be entangled with $\mathcal{H}$, relevant to weak gravitational interactions at or below the de Sitter scale of acceleration (e.g. 28)

$$a_{dS} = cH = 6.8 h_{70} \text{Å s}^{-2} \quad [3]$$

where $h_{70} = H/70\text{km s}^{-1}\text{Mpc}^{-1}$.

Our expression for Λ derives from the following elementary considerations.

In a radiation dominated universe, the total phase S is non-evolving, $S \equiv 0$, since all energy propagates along null-trajectories. With trivial transition amplitudes, the phase of the cosmological background is zero as in $\mathcal{M}$, whereby $S_0 = 0$. This gives a calibration point at deceleration parameter $q = 1$.

For S_0 of $\mathcal{H}$, an equivalent covariant scalar on cosmological background with scale factor $a(t)$ will be proportional to the Ricci scalar $R = R(a', a'')$. By explicit evaluation, $R = -6\lambda((a'/a)^2 2 + a''/a) = -6\lambda(1-q)H^2$.

The de Sitter limit $q = -1$ fixes the scale factor $\lambda = -1/6$ in three-flat cosmologies. The contribution S_0 of the cosmological vacuum hereby contributes 2Λ to the Lagrangian with $\Lambda = (1-q)H^2$ (27).

By direct integration (27), we arrive at (see also 12)

$$h(z) = (1+z)^{-1}\sqrt{1 + \frac{6}{5}\omega_m((1+z)^5 - 1)} \quad [4]$$

for $\Lambda = (1-q)H^2$. The equation of state parameter w of dark energy, relating dark pressure to dark energy $\Lambda/8\pi$, in these models is $w = -1$ in ΛCDM and $w = (2q-1)/(1-q)$ in Eq. (4).

Eqs. (2-4) share the same asymptotic behavior for large z covering the matter dominated era ($q = 1/2$ with $w = 0$) and radiation dominated era ($q = 1$). Different behavior appears as z becomes small.

While Eq. (4) is “asymptotically safe" in sharing the same behavior as ΛCDM at moderate to large z, it predicts enhanced accelerated cosmological expansion at z close to zero. De Sitter space ($q = -1$) is rendered unstable with a turning point in $H(z)$ at small z,

$$z_* = \left(\frac{5 - 6\omega_m}{9\omega_m}\right)^{\frac{1}{5}} - 1 \simeq 0.07 \pm 0.03 \quad [5]$$

with $q(z_*) = -1$ in light of $q(z) = -1 + (1+z)H'(z)/H(z)$, effectively prohibiting ΛCDM in the distant future as $z \to -1$. For the present epoch at low z, Eq. (5) points to strong curvature in $(z, H(z))$ well beyond what is expected in ΛCDM. Specifically, it satisfies $Q_0 \gtrsim 2.5$ versus $Q_0 \lesssim 1$ in ΛCDM, where $Q_0 = Q(0)$, $Q(z) = dq(z)/dz$ (27). This outcome carries a phanton-like dark energy ($w < -1$, e.g 7, 10, 16).

Confrontation with Pantheon data. In confronting potentially novel dynamics of Eq. (1) with data, H_0 serves as an overall scale factor while ω_m captures curvature in the graph $(z, H(z))$. By Eq. (1), any tension in H_0 with respect to the Planck value measured in ΛCDM analysis of the CMB brings along a correlated tension in ω_m according to $dH = 0$:

$$\Delta\omega_m = -\left(\frac{h'(z)}{h(z)}\right)^{-1}\frac{\Delta H_0}{H_0} \quad [6]$$

Fig. (2) shows illustrative results for $\Delta\omega_m$ associated with relative deviations of $\Delta H_0/H_0$ in fits by Eqs. (2-4), that would appear as expectation values in fits to data over a running interval centered at z.

Motivated by Eq. (5), we focus on estimates of ω_m estimates over relatively small redshift supernova data, obviating the need for an overall absolute magnitude calibration. We confront Eqs. (2-4) with the observed expansion of the Local Universe measured by supernovae of Pantheon (Fig. 1). To this end, we derive estimates of ω_m in fits by nonlinear model regression in (H_0, ω_m) over inner intervals $[0, z_{\max}]$ $(0 < z_{\max} \leq 2.26)$, complementary to the outer intervals $[z_{\min}, 0.25]$ in (21).

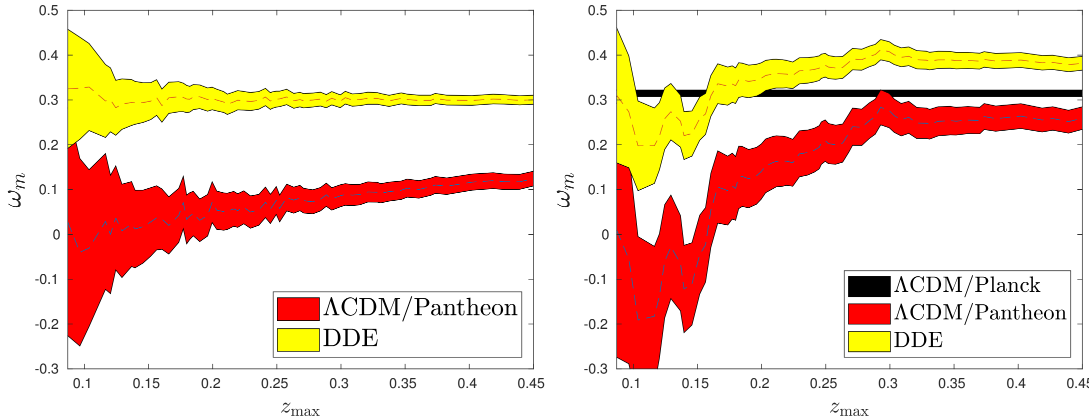

Fig. 3. (Left panel.) A Monte Carlo result on ω_m in a mock data analysis over inner intervals $[0, z_{\max}]$ by (2) of a cosmology with dynamical dark energy (4) and $\omega_m = 0.3$ in the presence of Gaussian noise of 0.1 magnitude STD. The widths of the curves refer to 1σ. The results indicate a downward trend in ω_m tension anticipated in ΛCDM fits to cosmologies with pronounced late time dark energy. (Right panel.) Estimates of ω_m in Pantheon data in fits by nonlinear model regression over $[0, z_{\max}]$ by both (2-4). The ΛCDM model fit produces ω_m with a strong drift away from the Planck value $\omega_m = 0.3147$ as z becomes small. Minor deviations appear in ω_m estimates for model fits (4).

Our fits use a nonlinear model regression method incorporated in the MatLab routine *fitnlm* (17), producing estimates of (H_0, ω_m) based on scattered data. We applying *fitnlm* over running intervals $[0, z_{\max}]$ $(0 < z_{\max} \leq 2.26)$ to model generated supernova magnitudes $\mu = 5\log_{10}(d_L/H_0) + C_0$, where

$$d_L(z, \omega_m) = (1+z)\int_0^z \frac{dz}{h(z,\omega_m)} \qquad [7]$$

is the luminosity distance and C_0 is a constant. For $0 < z_{\max} < 0.45$, we use essentially exact evaluation of d_L in a double series expansion of $1/h(z, \omega_m)$ in (z, ω_m) by symbolic computation up to order 20. For $z_{\max}$ covering the entire Pantheon range (that goes beyond the radius of convergence of series expansion in z of $1/h(z, \omega_m)$), we use numerical quadrature. Fits by (2-4) over the entire Pantheon data set $(z_{\max} = 2.26)$ produces the respective reference values

$$\omega_m = 0.2845 \pm 0.0125, \quad \omega_m = 0.3515 \pm 0.0086. \qquad [8]$$

Estimates ω_m thus obtained may also be compared with Planck (3):

$$\omega_m = 0.3147 \pm 0.0074, \qquad [9]$$

obtained from a ΛCDM analysis of the CMB.

Fig. (3) shows ω_m estimates over $[0, z_{\max}]$ in fits to (2-4) including (9). Fig. (4) shows deviations for these two results relative to (8-9).

Estimates of ω_m become markedly different in fits to data over intervals $[0, z_{\max}]$ with $z_{\max} << 1$. For $z_{\max} \simeq 0.145$, model fits (2-4) to Pantheon give

$$\omega_m = -0.17165 \pm 0.1041, \quad \omega_m = 0.1947 \pm 0.0570. \qquad [10]$$

For the ΛCDM fits by (2), our ω_m estimate at $z_{\max} = 0.145$ is in tension within Pantheon as a whole $(z_{\max} = 2.26)$ and Planck, at 4.3σ and, respectively, 4.6σ (Fig. 3). Fits to our late time quantum cosmology (4) gives a considerably smaller tension of 2.5σ and, respectively, 1.8σ at the same $z_{\max} = 1.45$.

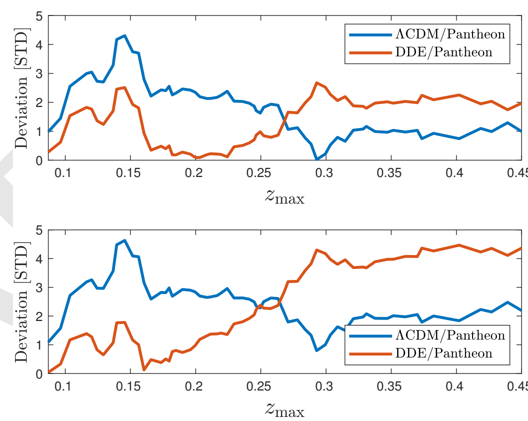

Fig. 4. Deviations by standard deviation of ω_m estimates in fits by nonlinear model regression to Pantheon data over intervals $[0, z_{\max}]$. (Upper panel.) Deviations in ω_m estimates relative to $\omega_m = 0.2845$ and $\omega_m = 0.3515$ in model fits to the full Pantheon data set $(z_{\max} = 2.26)$ by (2) and, respectively, (4). (Lower panel.) Deviations in ω_m estimates relative to the Planck value $\omega_m = 0.3147$ in fits by (2) and, respectively, (4).

Conclusions. High-resolution supernova surveys of the Local Universe such as Pantheon enable us to probe the nature of cosmological expansion *within* the same data set, independent of deviations from Planck, here demonstrated by analysis of ω_m. Deviations from ΛCDM are expected if de Sitter space is unstable as predicted by quantum cosmology. Exploiting the large Pantheon data set, ΛCDM is excluded by over 4.3σ, due to anomalous ω_m estimates at $z_{\max} = 0.145$ compared to its value defined by the entire Panteon data set $(z_{\max} = 2.26)$. This tension is independent of existing tension in the Hubble parameter with Planck and it occurs considerably below the effective redshift of other low z studies (cf. 4, 8). In contrast, late time quantum cosmology (4) is consistent with the Pantheon data to 2.5σ.

Surveys of the Local Universe are rapidly increasing in supernova counts by several orders of magnitude over the next few years (23). This development promises significant improvement in low z studies of the nature of dark energy such as explored here on the basis of the Pantheon data. Conceivably, future results will elucidate late time quantum cosmology in great detail pointed to by the present study.

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