Is Dark Energy Phantom-like?
What Do the Recent Observations Tell Us?

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Conclusion

I don't know :)

Based on

- Hazra, Majumdar, Pal, Panda, Sen: PRD (2015) [1310.6161]
- Adak, Majumdar, Pal: MNRAS (2014)

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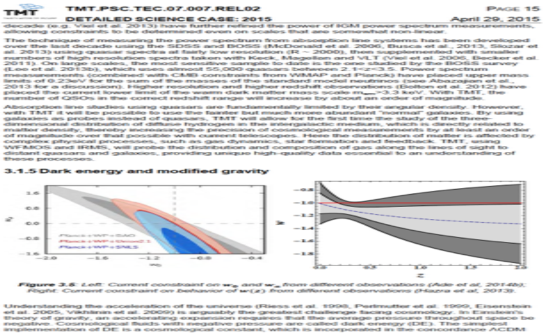
- Adak, Majumdar, Pal: MNRAS (2014)

Cited in Thirty Meter Telescope's Science Report 2015 together with Planck 2015 paper [1505.01195]



TMT.PSC.TEC.07.007.REL02 PAGE 15
DETAILED SCIENCE CASE: 2015 April 29, 2015

decade (e.g. Viel et al. 2013) have further refined the power of IGM power spectrum measurements, allowing constraints to be determined even on scales that are somewhat non-linear.

The technique of measuring the power spectrum from absorption line systems has been developed over the last decade using the SDSS and BOSS (McDonald et al. 2006, Busca et al., 2013, Slozar et al. 2013) using quasar spectra at fairly low resolution (R ~ 2000), then supplemented with smaller numbers of high resolution spectra taken with Keck, Magellan and VLT (Viel et al. 2006, Becker et al. 2011). On large scales, the most sensitive sample to date is the one studied by the BOSS survey (Lee et al. 2013b), which uses almost 55,000 quasars between 2.1<z<3.5. Power spectrum measurements (combined with CMB constraints from WMAP and Planck) have placed upper mass limits of 0.23eV for the sum of the masses of the standard model neutrinos (see Abazajian et al., 2013 for a discussion). Higher resolution and higher redshift observations (Bolton et al. 2012) have placed the current lower limit of the warm dark matter mass scale m>3.3 keV. With TMT, the number of QSOs in the correct redshift range will increase by about an order of magnitude.

Absorption line studies using quasars are fundamentally limited by their angular density. However, with TMT it will be possible to use the fainter but much more abundant "normal" galaxies. By using galaxies as probes instead of quasars, TMT will allow for the first time the study of the three-dimensional distribution of diffuse hydrogen in the intergalactic medium, which is directly related to matter density, thereby increasing the precision of cosmological measurements by at least an order of magnitude over that possible with current telescopes. Here the distribution of matter is affected by complex physical processes, such as gas dynamics, star formation and feedback. TMT, using WFMOS and IRMS, will probe the distribution and composition of gas along the lines of sight to distant quasars and galaxies, providing unique high-quality data essential to an understanding of these processes.

3.1.5 Dark energy and modified gravity

Figure 3.5: Left: Current constraint on w_0 and w_a from different observations (Ade et al, 2014b); Right: Current constraint on behavior of w(z) from different observations (Hazra et al, 2013).

Understanding the acceleration of the universe (Riess et al. 1998, Perlmutter et al. 1999, Eisenstein et al. 2005, Vikhlinin et al. 2009) is arguably the greatest challenge facing cosmology. In Einstein's theory of gravity, an accelerating expansion requires that the average pressure throughout space be negative. Cosmological fluids with negative pressure are called dark energy (DE). The simplest implementation of DE is a cosmological constant, which is incorporated in the concordance ΛCDM

Questions

- Is Dark Energy Equation of State unique?
- Is it observation dependent?
- Is it parametrization (theoretical prior) dependent?
- What can be the possible wayout?

Supernova Type Ia Data

Probe Luminosity distance: $D_L(z) = H_0 d_L(z)$ via distance modulus

$$\mu(z) = 5\log_{10}(D_L(z)) + \mu_0$$

$$\chi^2_{\rm SN}(w_X^0, \Omega_m^0, H_0) = \sum_i \left[\frac{\mu_{\rm obs}(z_i) - \mu(z_i; w_X^0, \Omega_m^0, H_0)}{\sigma_i}\right]^2$$

Marginalizing over the nuisance parameter μ_0,

$$\chi^2_{\rm SN}(w_X^0, \Omega_m^0) = A - B^2/C$$

$$A = \sum_i \left[\frac{\mu_{\rm obs}(z_i) - \mu(z_i; w_X^0, \Omega_m^0, \mu_0 = 0)}{\sigma_i}\right]^2$$

$$B = \sum_i \left[\frac{\mu_{\rm obs}(z_i) - \mu(z_i; w_X^0, \Omega_m^0, \mu_0 = 0)}{\sigma_i}\right]; C = \sum_i \frac{1}{\sigma_i^2}$$

Union 2.1 compilation of 580 Supernovae at $z = 0.015 - 1.4$, considered as standard candles

Baryon Acoustic Oscillation (BAO) data

Used to measure $H(z)$ and angular diameter distance $D_A(z)$ via a combination

$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)}\right]^{1/3}$$

Confront models via a distance ratio

$$d_z = \frac{r_s(z_{\rm drag})}{D_V(z)}$$

$r_s(z_{\rm drag})$ = comoving sound horizon at a redshift where baryon-drag optical depth is unity

Give 6 data points:

- WiggleZ : $z = 0.44, 0.6, 0.73$
- SDSS DR7 : $z = 0.35$
- SDSS DR9 : $z = 0.57$
- 6DF : $z = 0.106$

Hence calculate $\chi^2_{\rm BAO}$

Hubble Space Telescope Data (HST)

Use nearby Type-Ia Supernova data with Cepheid calibrations to constrain the value of H_0 directly.
Combine and calculate χ^2 for the analysis of HST data

$$\chi^2_{\rm HST}(w_X^0, \Omega_m^0, H_0) = \sum_i \left[\frac{H_{\rm obs}(z_i) - H(z_i; w_X^0, \Omega_m^0, H_0)}{\sigma_i}\right]^2$$

Two methods of analysis

- Riess et. al. (2011)
- Efstathiou (2014)

Cosmic Microwave Background (CMB) data

Reflection on Dark Energy

- CMB shift parameter (position of peaks)
- Integrated Sachs-Wolfe effect (low-ℓ)

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Shift Parameter

DE $\Leftrightarrow$ Shift in position of peaks by $\sqrt{\Omega_m}D$
D= Angular diameter distance (to LSS) $\Rightarrow$ Shift Parameter

$$R = \sqrt{\frac{\Omega_m h^2}{|\Omega_k| h^2}}\chi(y)$$

$$\chi(y) = \sin y(k < 0) \quad ; \quad = y(k = 0) \quad ; \quad = \sinh y(k > 0)$$

$$y = \sqrt{|\Omega_k|}\int_o^{z_{\rm dec}} \frac{dz}{\sqrt{\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_X(1+z)^{3(1+\omega_X)}}}$$

$$\chi^2_{\rm CMB}(\omega_X, \Omega_m, H_0) = \left[\frac{R(z_{\rm dec}, \omega_X, \Omega_m, H_0) - R}{\sigma_R}\right]^2$$

Integrated Sachs-Wolfe Effect

Some CMB anisotropies may be induced by passing through a time varying gravitational potential

- linear regime: integrated Sachs-Wolfe effect
- non-linear regime: Rees-Sciama effect

Poisson equation : $\nabla^2\Phi = 4\pi G a^2 \bar{\rho}\delta$

$\Phi \rightarrow$ constant during matter domination
$\rightarrow$ time-varying when dark energy comes to dominate
(at large scales $l \leq 20$)

$$C_l = \int \frac{dk}{k} P_R(k) T_l^2(k)$$
$$T_l^{\mathrm{ISW}}(k) = 2 \int d\eta \exp^{-\tau} \frac{d\Phi}{d\eta} j_l(k(\eta - \eta_0))$$

But cosmic variance !

Dark Energy Perturbations

Can be important at horizon scales.
Need to cross-correlate large scale CMB with large scale structures.

But cosmic variance!

Incorporated through sound speed squared c_s^2.
For canonical scalar, $c_s^2 = 1$

Dark energy parametrizations

- Parametrize the Hubble parameter
- Parametrize the Equation of State (EOS) of Dark Energy

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Parametrization of Hubble parameter

$$r(x) = \frac{H^2(x)}{H_0^2} = \Omega_m^0 x^3 + A_0 + A_1 x + A_2 x^2$$

with $x = 1 + z \;\; ; \;\; \Omega_m^0 + A_0 + A_1 + A_2 = 1 \;\; ; \;\; \rho_c^0 = 3H_0^2$

$$\rho = \rho_c^0 \left(A_0 + A_1 x + A_2 x^2 \right)$$

- For $A_0 \neq 0, A_1 = 0 = A_2 \Longrightarrow \Lambda$CDM
- Either $A_1 \neq 0$ or $A_2 \neq 0 \Longrightarrow$ Dynamical dark energy

Parametrization of EOS

• CPL Parametrization

Fits a wide range of scalar field dark energy models including the supergravity-inspired SUGRA dark energy models.

$$
\begin{aligned}
w(a) &= w_0 + w_{\rm a}(1-a) \\
&= w_0 + w_{\rm a}\frac{z}{1+z}
\end{aligned}
$$

$$\rho_{\rm DE} \propto a^{-3(1+w_0+w_{\rm a})} e^{-3w_{\rm a}(1-a)}$$

- Two parameter description: $w_0 =$ EOS at present , $w_{\rm a} =$ its variation w.r.t. scale factor (or redshift).
- For $w_0 \geq -1, w_a > 0$: dark energy is non-phantom throughout
- Otherwise, may show phantom behavior at some point

• SS Parametrization

Useful for slow-roll ‘thawing’ class of scalar field models having a canonical kinetic energy term.
Motivation : to look for a unique dark energy evolution for scalar field models that are constrained to evolve close to Λ.

$$w(a) = (1 + w_0) \times$$
$$\left[\sqrt{1 + (\Omega_{\rm DE}^{-1} - 1)a^{-3}} - (\Omega_{\rm DE}^{-1} - 1)a^{-3} \tanh^{-1} \frac{1}{\sqrt{1+(\Omega_{\rm DE}^{-1}-1)a^{-3}}}\right]^2 \times$$
$$\left[\frac{1}{\sqrt{\Omega_{\rm DE}}} - \left(\frac{1}{\Omega_{\rm DE}} - 1\right) \tanh^{-1} \sqrt{\Omega_{\rm DE}}\right]^{-2} - 1$$

- One model parameter: w_0 = EOS at present
- Rest is taken care of by the general cosmological parameter $\Omega_{\rm DE}$ = dark energy density today.

- ## GCG Parametrization

$$p = -\frac{c}{\rho^{\alpha}}$$

$$w(a) = -\frac{A}{A+(1-A)a^{-3(1+\alpha)}} \;;\; A = \frac{c}{\rho_{\mathrm{GCG}}^{1+\alpha}}$$

- Two model parameters e.g A and α, with $w(0) = -A$
- For $(1+\alpha) > 0$, $w(a)$ behaves like a dust in the past and evolves towards negative values and becomes $w = -1$ in the asymptotic future. $\Longrightarrow$ 'tracker/freezer' behavior
- For $(1+\alpha) < 0$, $w(a)$ is frozen to $w = -1$ in the past and it slowly evolves towards higher values and eventually behaves like a dust in the future. $\Longrightarrow$ 'thawing' behavior
- Restricted to $0 < A < 1$ only since for $A > 1$ singularity appears at finite past $\Longrightarrow$ non-phantom only

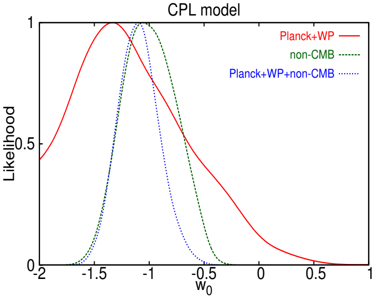
Dark energy from different datasets

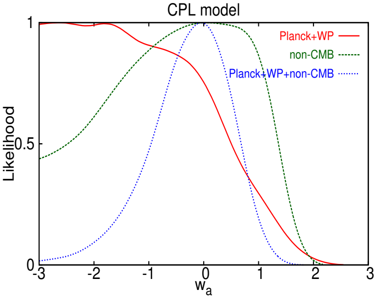
Used all three parametrizations $\Longrightarrow$ Analysis is robust

Data	ΛCDM	CPL	SS	GCG
Planck (low-ℓ + high-ℓ)	7789.0	7787.4	7788.1	7789.0
WMAP-9 low-ℓ polarization	2014.4	2014.436	2014.455	2014.383
BAO : SDSS DR7	0.410	0.073	0.265	0.451
BAO : SDSS DR9	0.826	0.793	0.677	0.777
BAO : 6DF	0.058	0.382	0.210	0.052
BAO : WiggleZ	0.020	0.069	0.033	0.019
SN : Union 2.1	545.127	546.1	545.675	545.131
HST	5.090	2.088	2.997	5.189
Total	10355.0	10351.4	10352.4	10355.0

Best fit $\chi^2_{\rm eff}$ obtained in different model upon comparing against CMB + non-CMB datasets using the Powell's BOBYQA method of iterative minimization.

Likelihood functions for CPL parametrization





Concordance with Planck 2015 paper: CPL

Planck Collaboration: *Planck* 2015 results. XIV. Dark energy and modified gravity

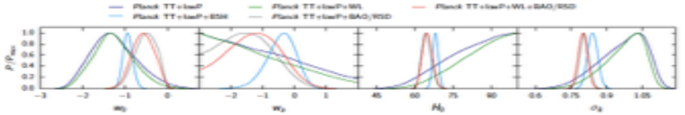


Fig. 3. Parameterization $\{w_0, w_a\}$ (see Sect. 5.1.1). Marginalized posterior distributions for w_0, w_a, H_0 and σ_8 for various data combinations. The tightest constraints come from the *Planck* TT+lowP+BSH combination, which indeed tests background observations, and is compatible with ΛCDM.

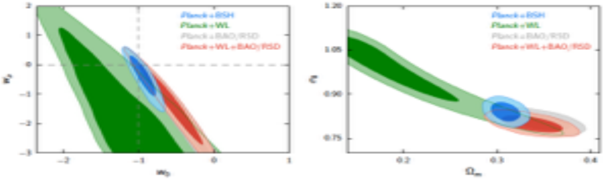


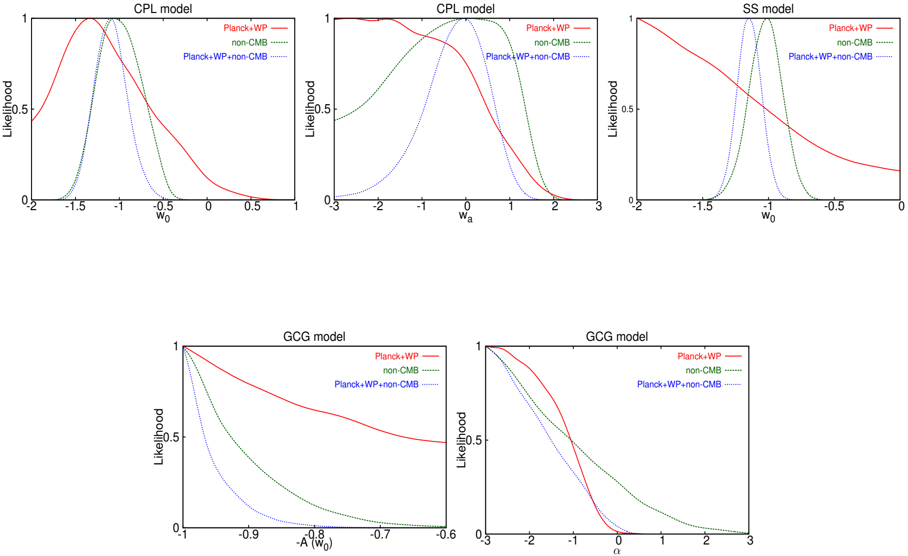
Fig. 4. Marginalized posterior distributions of the (w_0, w_a) parameterization (see Sect. 5.1.1) for various data combinations. The best constraints come from the priority combination and are compatible with ΛCDM. The dashed lines indicate the point in parameter space $(-1, 0)$ corresponding to the ΛCDM model. CMB lensing and polarization do not significantly change the constraints. Here *Planck* indicates *Planck* TT+lowP.

these probes are weaker, since we are considering a smooth dark energy model where the perturbations are suppressed on small scales. While the WL data appear to be in slight tension with ΛCDM, according to the green contours shown in Fig. 4, the difference in total χ^2 between the best-fit in the $\{w_0, w_a\}$ model

powers of the scale factor up to order N:

$$w(a) = w_0 + \sum_{i=1}^{N} (1-a)^i w_i . \quad (19)$$

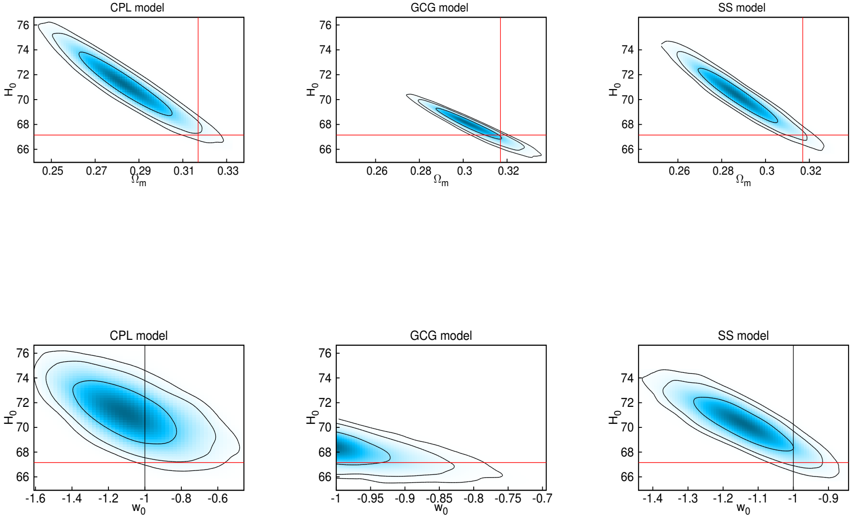
Likelihood functions for different parameters of EOS



Mean value and 1σ range for CMB+non-CMB

		CPL	SS	GCG
$\Omega_b h^2$	CMB	0.0221 ± 0.00028	0.0221 ± 0.00026	0.022 ± 0.00028
	CMB + non-CMB	0.022 ± 0.00026	$0.0221^{+0.00026}_{-0.00024}$	0.0223 ± 0.00024
	Non-CMB	$0.027^{+0.004}_{-0.005}$	$0.028^{+0.004}_{-0.006}$	0.029 ± 0.005
$\Omega_{CDM} h^2$	CMB	0.1196 ± 0.0027	0.1198 ± 0.0026	$0.1199^{+0.0026}_{-0.0028}$
	CMB + non-CMB	0.1209 ± 0.0023	0.1192 ± 0.0018	0.117 ± 0.0015
	Non-CMB	$0.126^{+0.014}_{-0.017}$	$0.128^{+0.014}_{-0.018}$	$0.127^{+0.015}_{-0.018}$
100θ	CMB	1.041 ± 0.0006	1.041 ± 0.0006	1.041 ± 0.0006
	CMB + non-CMB	1.041 ± 0.0006	1.041 ± 0.00056	1.042 ± 0.00056
	Non-CMB	1.042 ± 0.023	1.048 ± 0.022	$1.05^{+0.019}_{-0.027}$
τ	CMB	$0.09^{+0.012}_{-0.014}$	$0.09^{+0.012}_{-0.015}$	$0.09^{+0.013}_{-0.014}$
	CMB + non-CMB	$0.087^{+0.012}_{-0.014}$	0.091 ± 0.013	0.094 ± 0.014
	Non-CMB	...	...	...
$w_0[-A]$	CMB	$-1.13^{+0.37}_{-0.66}$	$-1.31^{+0.19}_{\text{unbounded}}$	$-0.827^{+0.06}_{\text{non-phantom prior cut}}$
	CMB + non-CMB	$-1.005^{+0.15}_{-0.17}$	$-1.14^{+0.08}_{-0.09}$	$-0.957^{+0.007}_{\text{non-phantom prior cut}}$
	Non-CMB	$-0.995^{+0.23}_{-0.27}$	-1.02 ± 0.12	$-0.92^{+0.018}_{\text{non-phantom prior cut}}$
$w_a[\alpha]$	CMB	$-1.15^{+0.6}_{\text{unbounded}}$	...	$-1.97^{+0.32}_{\text{unbounded}}$
	CMB + non-CMB	$-0.48^{+0.77}_{-0.54}$	...	$-2.0^{+0.29}_{\text{unbounded}}$
	Non-CMB	$-0.5^{+1.64}_{-0.94}$	...	$-1.49^{+0.4}_{\text{unbounded}}$
n_S	CMB	0.9607 ± 0.007	0.9603 ± 0.007	$0.9603 \pm +0.00073$
	CMB + non-CMB	$0.9579^{+0.0063}_{-0.0066}$	$0.9619^{+0.0059}_{-0.0057}$	$0.9669^{+0.00056}_{-0.00059}$
	Non-CMB	...	...	...
$\ln[10^{10} A_S]$	CMB	$3.089^{+0.023}_{-0.027}$	$3.089^{+0.023}_{-0.028}$	3.09 ± 0.025
	CMB + non-CMB	$3.087^{+0.024}_{-0.026}$	3.091 ± 0.025	3.092 ± 0.026
	Non-CMB	...	...	...
Ω_m	CMB	$0.239^{+0.028}_{-0.099}$	$0.27^{+0.04}_{-0.1}$	$0.344^{+0.022}_{-0.032}$
	CMB + non-CMB	$0.291^{+0.011}_{-0.013}$	$0.288^{+0.012}_{-0.013}$	$0.304^{+0.009}_{-0.011}$
	Non-CMB	0.29 ± 0.024	$0.298^{+0.02}_{-0.026}$	$0.3^{+0.021}_{-0.024}$
H_0	CMB	$80^{+17.8}_{-7.8}$	$74.8^{+13.3}_{-9.8}$	$64.6^{+2.61}_{-1.91}$
	CMB + non-CMB	70.26 ± 1.4	70.3 ± 1.4	$67.9^{+0.9}_{-0.7}$
	Non-CMB	72.68 ± 2.2	72.67 ± 2.15	72.4 ± 2.16

Analysis: value of H_0



- If phantom is forbidden by theoretical prior (GCG):
  - The parameters stay close to the values obtained in ΛCDM model analysis.
  - H_0 is not that degenerate with dark energy equation of state for CMB.

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  - The parameters stay close to the values obtained in ΛCDM model analysis.
  - H_0 is not that degenerate with dark energy equation of state for CMB.
- If phantom is not forbidden by theoretical prior (CPL+SS):
  - Better fit to the CMB data comes with a large value of H_0 $\Rightarrow$ agrees better with the HST data (better total χ^2)
  - But background cosmological parameter space (e.g., $\Omega_{\rm m} - H_0$) is dragged s.t. best-fit base model and that from Planck becomes 2σ away.
  - H_0 becomes highly degenerate with dark energy EOS for CMB only measurements.

Comparison with Planck 2015

Difference in analysis of HST data : Riess vs Efstathiou

ple[3] are discussed by Betoule et al. (2014), and as mentioned in Planck Collaboration XIII (2015) the constraints are consistent with the 2013 and 2104 *Planck* values for standard ΛCDM.

4.2.3. The Hubble constant

The CMB measures mostly physics at the epoch of recombination, and so provides only weak direct constraints about low-redshift quantities through the integrated Sachs-Wolfe effect and CMB lensing. The CMB-inferred constraints on the local expansion rate H_0 are model dependent, and this makes the comparison to direct measurements interesting, since any mismatch could be evidence of new physics.

Here, we rely on the re-analysis of the Riess et al. (2011) (hereafter R11) Cepheid data made by Efstathiou (2014) (hereafter E14). By using a revised geometric maser distance to NGC 4258 from Humphreys et al. (2013), E14 obtains the following value for the Hubble constant:

$$H_0 = (70.6 \pm 3.3)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}, \tag{10}$$

which is within 1σ of the *Planck* TT+lowP estimate. In this paper we use Eq. (10) as a conservative H_0 prior. We note that the 2015 *Planck* TT+lowP value is perfectly consistent with the 2013 *Planck* value (Planck Collaboration XVI 2014) and so the tension with the R11 H_0 determination is still present at about 2.4σ. We refer to the cosmological parameter paper Planck Collaboration XIII (2015) for a more comprehensive discussion of the different values of H_0 present in the literature.

where σ_8 is calculated including all matter and neutrino density perturbations. Anisotropic clustering also contains geometric information from the Alcock-Paczynski (AP) effect (Alcock & Paczynski 1979), which is sensitive to

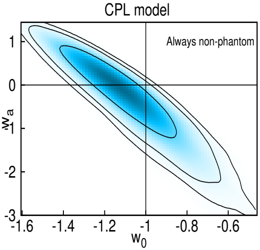
$$F_{AP}(z) = (1+z)D_A(z)H(z)\,. \tag{12}$$

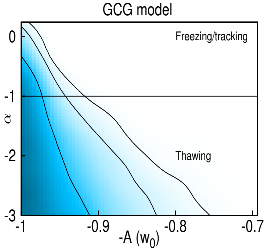
In addition, fits which constrain RSD frequently also measure the BAO scale, $D_V(z)/r_s$, where r_s is the comoving sound horizon at the drag epoch, and D_V is given in Eq. (9). As in Planck Collaboration XIII (2015) we consider only analyses which solve simultaneously for the acoustic scale, F_{AP} and $f\sigma_8$.

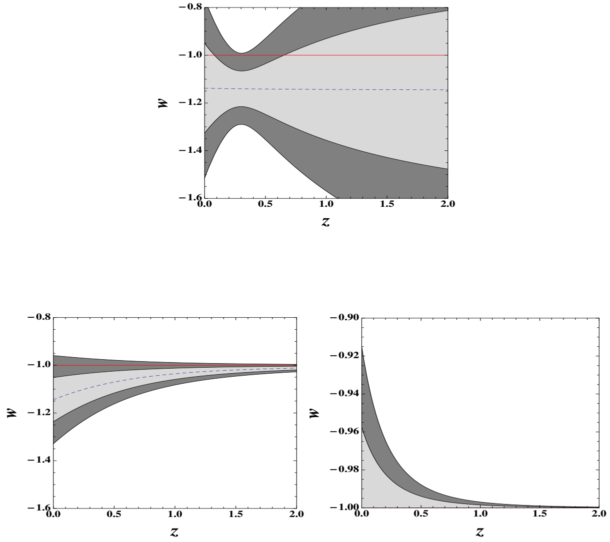
The Baryon Oscillation Spectroscopic Survey (BOSS) collaboration have measured the power spectrum of their CMASS galaxy sample (Beutler et al. 2014) in the range $k = 0.01$–$0.20\,h\,\mathrm{Mpc}^{-1}$. Samushia et al. (2014) have estimated the multipole moments of the redshift-space correlation function of CMASS galaxies on scales $> 25\,h^{-1}$Mpc. Both papers provide tight constraints on the quantity $f\sigma_8$, and the constraints are consistent. The Samushia et al. (2014) result was shown to behave marginally better in terms of small-scale bias compared to mock simulations, so we choose to adopt this as our baseline result. Note that when we use the data of Samushia et al. (2014), we exclude the measurement of the BAO scale, D_V/r_s, from Anderson et al. (2013), to avoid double counting.

The Samushia et al. (2014) results are expressed as a 3×3 covariance matrix for the three parameters D_V/r_s, F_{AP} and $f\sigma_8$, evaluated at an effective redshift of $z_{eff} = 0.57$. Since Samushia et al. (2014) do not apply a density field reconstruction in their analysis, the BAO constraints are slightly weaker than, though consistent with, those of Anderson et al. (2014).

Analysis: Equation of State







Top: CPL, Bottom left: SS, Bottom right: GCG

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- If phantom is not forbidden by theoretical prior (CPL+SS):
  - CMB data: the non-phantom equation of states stays at the edge of 2σ region.
  - Non-CMB data: non-phantom behavior favored for every parametrization considered.

Combined CMB + non-CMB data

Mean w and error bar depends on the parametrization.

- SS and GCG parametrization: the nature of dark energy is best constrained at high redshifts
- CPL parametrization: the best constraints come in the redshift range of $\approx 0.2 - 0.3$

Just as aside...

- Similar results by Novosyadlyj et.al. (JCAP): for dataset Planck+HST+BAO+SNLS3 ΛCDM is outside 2σ confidence regime, for dataset WMAP-9+HST+BAO+SNLS3 ΛCDM is 1σ away from best fit.
- PAN-STARRS1 shows tension with ΛCDM at 2.4σ with a constant EOS (Rest et.al., 1310.3828)

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- Can it be due to lack of a better theory/parametrization of the dark energy equation of state?

  Most likely yes

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- Can it be due to different analysis of HST data (Riess vs Efsthathiou)?

  Maybe
- Can it be due to lack of a better theory/parametrization of the dark energy equation of state?

  Most likely yes
- Can a non-parametric reconstruction of w for the total dataset help to infer about the correct nature of dark energy (or, Λ) without any priors on the form of w?

Conclusion

I don't know :)