Lambda or not too Lambda?

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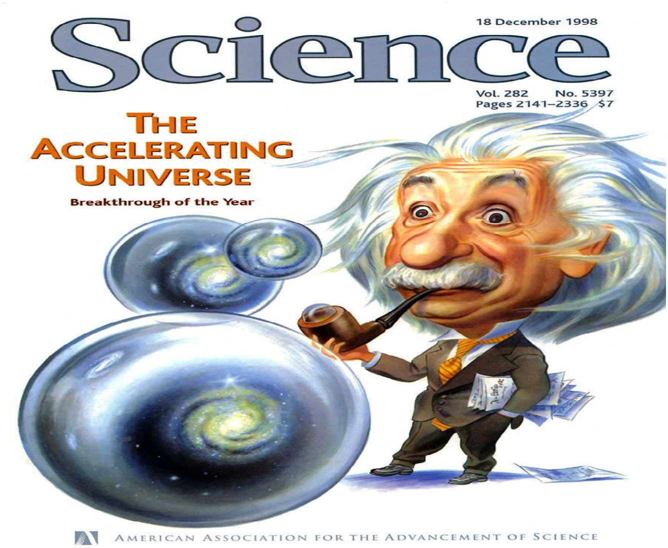
Conclusion

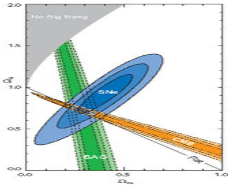
We don't know :)

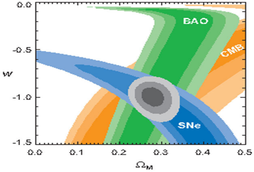
Some random questions

- Why is this surprising?
- How do we describe different dark energy models in a common language?
- How do we extract information about dark energy from different observations?
- What is our current understanding of dark energy?
- How conclusive is our understanding?

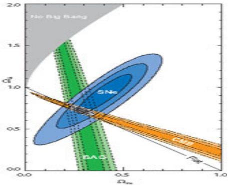
A bit of history

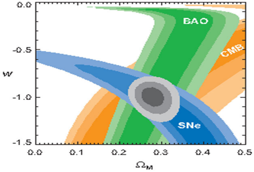






Universe is accelerating at present





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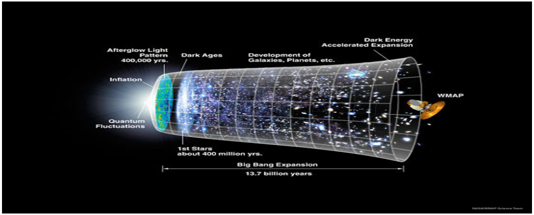
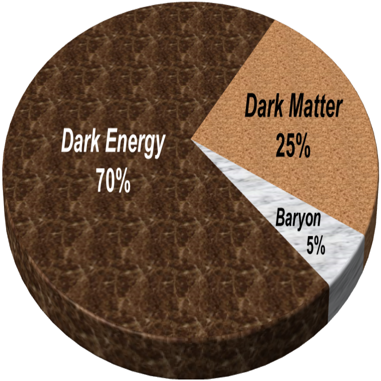


This is a recent phenomenon

Cosmic budget



Why is this surprising?

Gravitational force is attractive

$\downarrow$

Theory of gravitation: General Relativity

$\downarrow$

Evolution of the Universe: Friedmann equations

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

$\downarrow$

Universe should decelerate

Ordinary matter satisfying Strong Energy Condition $(\rho + 3p) \geq 0$ cannot supply the effective "anti-gravity" required for acceleration!

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Ordinary matter satisfying Strong Energy Condition $(\rho + 3p) \geq 0$ cannot supply the effective "anti-gravity" required for acceleration!

If it's not surprising enough, it's not fun!

Candidate Type 1: Cosmological Constant

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{a^2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

$$M = \frac{4}{3}\pi a^3(\rho + 3p) \Longrightarrow \qquad \ddot{a} = -\frac{GM}{a^2} + \frac{\Lambda}{3}a$$

$M \downarrow$ Effective mass; $-\frac{GM}{a^2} \swarrow$ Attraction; $\frac{\Lambda}{3}a \searrow$ Repulsion

$$a(t) \propto \left[\sinh\left(\frac{3}{2}\sqrt{\frac{\Lambda}{3}}t\right)\right]^{2/3}$$

- Fine-tuning problem $\sim 10^{121}$
- Cosmic coincidence problem
- .....

Candidate Type 2: Dynamical models

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\sum_i \rho_i - \frac{k}{a^2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\sum_i (\rho_i + 3p_i)$$

$p_i < -\rho_i/3 \Rightarrow w_i < -1/3$ leads to acceleration $\Longleftrightarrow$ violates SEC

Scalar field models

EM tensor components $\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$; $p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$

- Quintessence: scalar field minimally coupled to gravity
- K-essence: Kinetic energy driven
- Tachyonic: Non-canonical
- Phantom: Opposite sign in kinetic term
- Dilatonic
- (Generalized) Chaplygin gas
- .....

Candidate Type 3: Modified gravity models

* Einstein's theory is not directly tested in cosmological scales.
* Modify the gravity sector rather than the matter sector.

- Brans-Dicke theory: G as a VEV of a geometric field, need vastly different values for solar system and cosmic scales
- f(R) gravity: R in the action replaced by f(R), [e.g. $R - \frac{\mu}{R}$], no unique choice
- DGP model: Extra dimensional effects at large scale, fails to produce small scale results
- ......

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- ......

Bottomline: Too many models!

From models to parametrizations

Data is only sensitive to some parameters.
Using data, we cannot directly constrain a model, we can constrain only the parameters of the background model.

Proposal

Instead of proposing individual models, can we parametrize dark energy and constrain models from observations by constraining those parameters?

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Proposal

Instead of proposing individual models, can we parametrize dark energy and constrain models from observations by constraining those parameters?

Observationally we probe 2 (3) parameters of dark energy:

- Density parameter ($\Omega_{\rm DE}$) (by probing $\Omega_{\rm M}$)
- Equation of State (EOS) parameter ($w_{\rm DE}$)
- Sound speed ($C_{\rm s,DE}$) (if perturbations included)

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

• CPL Parametrization

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

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

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

- 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.

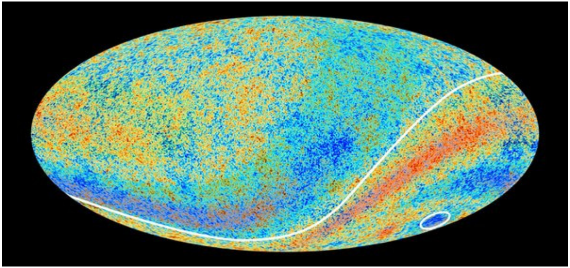
- GCG Parametrization

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

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

- 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

Cosmic Microwave Background (CMB) data



Background temperature $T_0 = 2.725K$ at all directions

$\Rightarrow$ The Universe is homogeneous and isotropic at largest scale

All about CMB temperature

Background : $T_0 = 2.725K \longrightarrow$ Blackbody spectrum

Fluctuations : $-200\mu K < \Delta T < 200\mu K$

$$\Delta T_{rms} \sim 70\mu K$$

$$\Delta T_{pE} \sim 5\mu K$$

$$\Delta T_{pB} \sim 10 - 100nK$$

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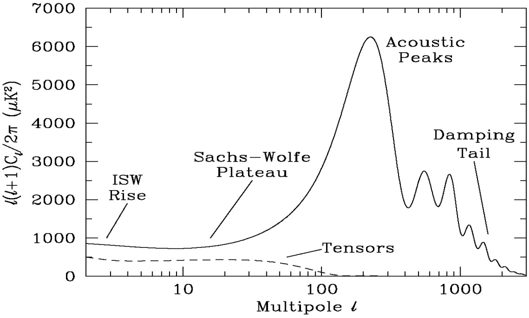
How to decode information?



Cosmological parameters from CMB

Fundamental/ fit parameters

$\Omega_b h^2$ = baryonic matter density
$\Omega_c h^2$ = dark matter density
Ω_X = dark energy density
A_s = amplitude of scalar power spectrum
n_s = scalar spectral index
τ = optical depth
r = tensor-to-scalar ratio

Altogether 6 (or 7 if $r \neq 0$)

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$$\begin{aligned}
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\tau &= \text{optical depth} \\
r &= \text{tensor-to-scalar ratio}
\end{aligned}$$

Altogether 6 (or 7 if $r \neq 0$)

Derived parameters

$$t_0,\ H_0,\ \Omega_b,\ \Omega_c,\ \Omega_m,\ \Omega_k,\ \Omega_{\rm tot},\ \sigma_8,\ z_{\rm eq},\ z_{\rm reion}\ldots$$

Planck 2015 highlights

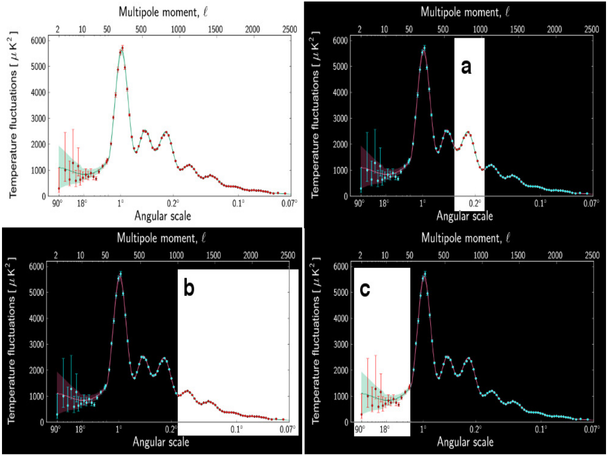
Ade et.al., 1502.01589; 1502.01590; 1502.01592; 1502.00612

Parameters	Planck2015 TT+low P	Planck2015 TT,TE,EE+low P
$\Omega_b h^2$	0.02222 ± 0.00023	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1198 ± 0.0015
Ω_M	0.315 ± 0.013	0.3156 ± 0.0091
$\ln(10^{10} A_S)$	3.089 ± 0.036	3.094 ± 0.034
n_s	0.9655 ± 0.0062	0.9645 ± 0.0049
τ	0.078 ± 0.019	0.079 ± 0.017
H_0	67.31 ± 0.96	67.27 ± 0.66
σ_8	0.829 ± 0.014	0.831 ± 0.013
r	< 0.11	< 0.07 (+BICEP2 Keck)

NG Parameters	Planck2015 TT	Planck2015 TT+low P
$f_{\mathrm{NL}}^{\mathrm{loc}}$	2.5 ± 5.7	0.8 ± 5.0
$f_{\mathrm{NL}}^{\mathrm{eq}}$	-16 ± 70	-4 ± 43
$f_{\mathrm{NL}}^{\mathrm{ortho}}$	-34 ± 33	-26 ± 21

CMB: Reflection on Dark Energy

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



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!

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 (latest: JLA=SDSS-II+SNLS)

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

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

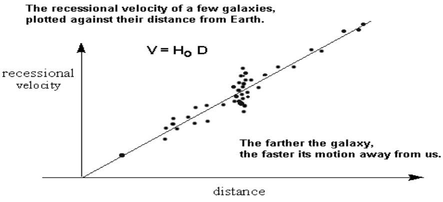
$r_s(z_{\rm drag})$ = comoving sound horizon at a redshift where baryon-drag optical depth is unity

Give 8 data points:

- WiggleZ : $z = 0.44, 0.6, 0.73$
- 6dFGS : $z = 0.106$
- SDSS MGS: $z = 0.15$
- BOSS DR12: $z = 0.38, 0.51, 0.61$

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

Hubble Space Telescope Data (HST)



On this graph, the slope of the line is equal to Hubble's Constant (H_0)

Constrains the value of H_0 directly by using nearby Type-Ia Supernova data with Cepheid calibrations.

Combine and calculate χ^2 for the analysis of HST data

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

Different analysis and dataset

- Riess et. al., 2011 (R11)
- Efstathiou, 2014 (E14)
- Riess et. al., 2016 (R16)

Dark energy from different datasets

Hazra, Majumdar, SP, Panda, Sen: PRD:2015

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

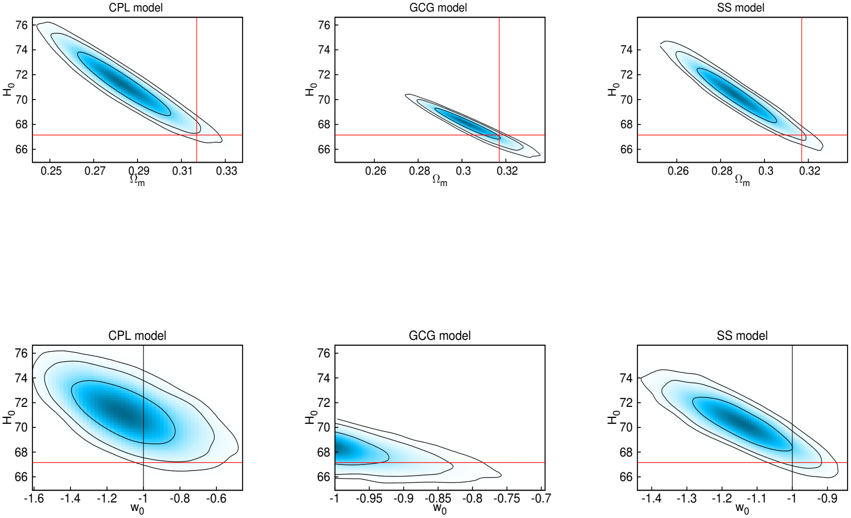
Best fit χ^2_{eff} obtained in different model upon comparing against CMB + non-CMB datasets using the Powell's BOBYQA method of iterative minimization.

Used all three parametrizations $\Longrightarrow$ The analysis is robust

Parameters (mean value with 1σ)

		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: H_0


CPL model
GCG model
SS model
H0
Ωm
76
74
72
70
68
66
0.25
0.27
0.29
0.31
0.33
0.26
0.28
0.3
0.32
CPL model
GCG model
SS model
H0
w0
-1.6
-1.4
-1.2
-1
-0.8
-0.6
-0.95
-0.9
-0.85
-0.8
-0.75
-0.7
-1.3
-1.1
-0.9

- 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
    - But background cosmological parameter space (e.g., $\Omega_{\rm m} - H_0$) is dragged s.t. best-fit base model and that analyzed by Planck becomes 2σ away.
    - H_0 is highly degenerate with dark energy EOS for CMB only measurements.

Concordance with Planck 2015 paper

"...and so the tension (of 2015 Planck TT + lowP) with R11 H_0 determination is still present at about 2.4σ" – Planck 2015 paper.

Catch: 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:

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

which is within $1\,\sigma$ 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 $2.4\,\sigma$. 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

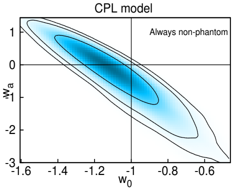
$$F_{AP}(z) = (1+z)D_A(z)H(z)\,. \quad (12)$$

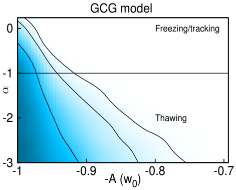
In addition, fits which constrain RSD frequently also measure the BAO scale, $D_V(z)/r_s$, where r_s is the comoving sound horizon at the drag epoch, and D_V is given in Eq. (9). As in Planck Collaboration XIII (2015) we consider only analyses which solve simultaneously for the acoustic scale, F_{AP}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

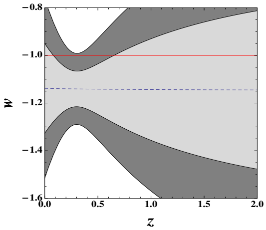
The Baryon Oscillation Spectroscopic Survey (BOSS) collaboration have measured the power spectrum of their CMASS galaxy sample (Beutler et al. 2014) in the range $k = 0.01$–$0.20\,h\,\mathrm{Mpc}^{-1}$. Samushia et al. (2014) have estimated the multipole moments of the redshift-space correlation function of CMASS galaxies on scales $> 25\,h^{-1}\mathrm{Mpc}$. 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).

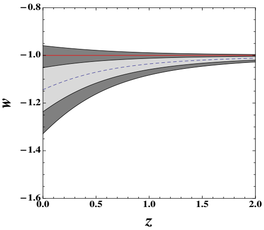
Analysis: Equation of State



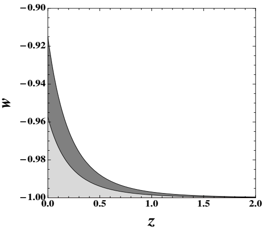




CPL



SS



GCG

- If phantom is forbidden by theoretical prior (GCG):
    - CMB and non-CMB observations are separately sensitive to the model parameters but the joint constraint is consistent with ΛCDM.
    - But they have marginally worse likelihood than other parametrizations.

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  - But they have marginally worse likelihood than other parametrizations.
- If phantom is **NOT** forbidden by theoretical prior (CPL+SS):
  - CMB data: the non-phantom EOS (and hence ΛCDM) stays at the edge of 2σ region.
  - Non-CMB data: non-phantom behavior favored for every parametrization considered.

Thirty Meter Telescope's Science Report 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_{wdm}>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

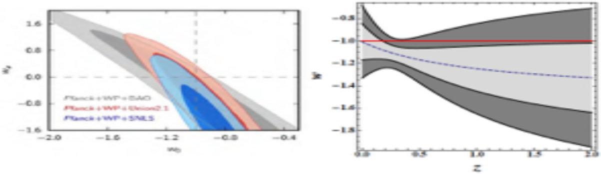

Figure 3.5: *Left: Current constraint on w_0 and w_a from different observations (Ade et al, 2014b); Right: Current constraint on behavior of $w(z)$ from different observations (Hazra et al, 2013).*

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

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  Unlikely!
- Can it be due to degeneracy between H_0 and other parameters?

  Most likely yes
- Can it be due to lack of better understanding of dark energy EOS, i.e., non-availability of data at relatively high redshift?

  Yes, in all probability

Oops! Some more in the queue

- Parallel analysis : Planck13(WMAP9)+ HST+BAO+SNLS3 ΛCDM is outside 2σ (1σ) confidence regime.

  Durrer et.al., JCAP:2013

- Alternative analysis : Discripancy attributed to the mismatch of value of H_0 due to degeneracy with other parameters ($\Delta N_{\rm eff}, r_s, Y_{\rm BBN}\ldots$)

  Riess et.al., JCAP:2016

- Some other datasets in tension with ΛCDM:

  PAN-STARRS1 data $\rightarrow 2.4\sigma$ Rest et.al., ApJ:2013

  Lyα BAO data ($z = 2.34$) $\rightarrow 2.5\sigma$

  Lensing amplitude $\rightarrow A_L = 1.22 \pm 0.10$ (Planck TT + low P)

  H0LiCOW data $\rightarrow 4.2\sigma$ Suyu et.al., MNRAS:2016

Who is the main culprit?

Bhattacharyya, Alam, Pandey, Das, SP:1805.04716

- H_0 tension

Dataset	Value: km/s/Mpc
WMAP9	69.7 ± 2.1
Riess 2011	72.8 ± 2.4
Planck 2013	67.3 ± 1.2
Efstathiou 2014	70.6 ± 3.3
Planck 2015	67.3 ± 1.0
Riess 2016	73.24 ± 1.74

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- σ_8 ($8h^{-1}$Mpc) tension

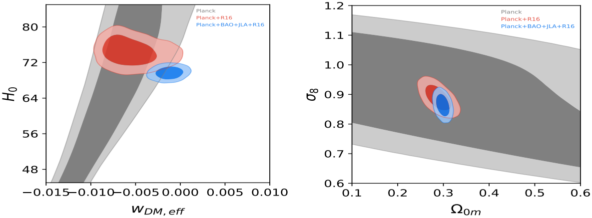
Dataset	Value $\sigma_8\sqrt{\Omega_{0m}/0.3}$
Planck 2015	0.851 ± 0.013
Clusters (X-ray)	0.745 ± 0.039
Weak lensing	0.75 ± 0.04

Generic Parametrization Scheme

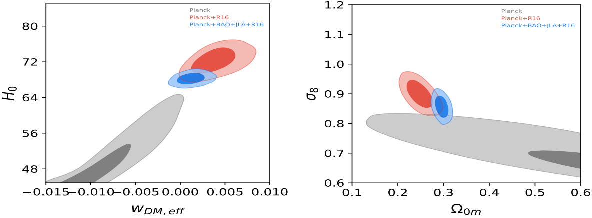
- Consider most generic situation: two fluids (DM-DE), interacting, both perturbed
- Write down background and perturbation equations
- Parametrization: $\{w_{DM,eff}, w_{DE,eff}, C^2_{sDM,eff}, C^2_{sDE,eff}\}$
- Boils down to different models for specific choice
  - $w_{DM,eff} = 0, w_{DE,eff} = -1, C^2_{sDM,eff} = 0, C^2_{sDE,eff} = 0$ $\Rightarrow$ ΛCDM
  - $w_{DM,eff} = 0, w_{DE,eff} > -1, C^2_{sDM,eff} = 0, C^2_{sDE,eff} = 1$ $\Rightarrow$ non-phantom, w_zCDM
  - $w_{DM,eff} = 0, w_{DE,eff} < -1, C^2_{sDM,eff} = 0, C^2_{sDE,eff} = 1$ $\Rightarrow$ phantom, w_zCDM
  - $w_{DM,eff} = 0, w_{DE,eff} < -1, C^2_{sDM,eff} = 0, C^2_{sDE,eff} \neq 1$ $\Rightarrow$ modified gravity
  - $w_{DM,eff} \neq 0, w_{DE,eff} = -1, C^2_{sDM,eff} = 0, C^2_{sDE,eff} = 1$ $\Rightarrow$ warm dark matter
  - $w_{DM,eff} \neq 0, w_{DE,eff} < -1 or > -1, C^2_{sDM,eff} \neq 0, C^2_{sDE,eff} \neq 1$ $\Rightarrow$ interacting DM-DE
- Constrain these parameters from data

Major results

Phantom

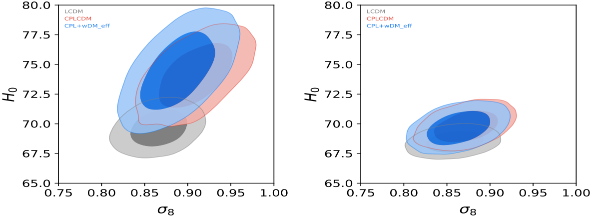


Non-phantom

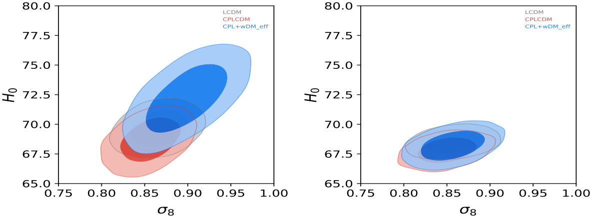


Correlation between H_0 and σ_8

Phantom



Non-phantom



Strong positive correlation between H_0 and σ_8 is generic to present cosmological data

Some more probes

- Weak lensing
- Galaxy cluster abundance
- Gamma ray bursts
- X-ray observations
- Lyman α
- Growth factor
- 21 cm observations (SKA)
- Cosmic shear and sound speed (TMT)
- ....

Take-home message

The point is not to pocket the truth but to chase it