Constraints on dynamical dark energy models from CMB, BAO and Growth Rate Measurements

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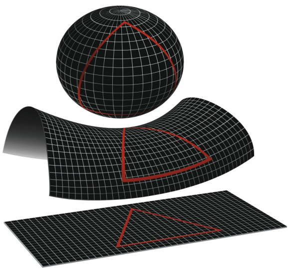
Introduction



- **Homogeneidad:** Invarianza bajo traslación (densidad media)
- **Isotropía:** Invarianza bajo rotación (direcciones de observación)

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right]$$

Friedmann equations:

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

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p/c^2)$$

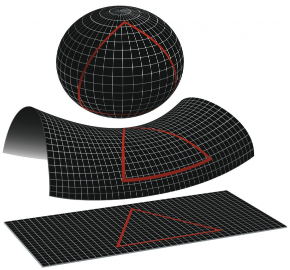
$$\Omega_m + \Omega_\Lambda + \Omega_k = 1$$

$$H^2 = H_0^2\left(\Omega_{m,0}a^{-3} + \Omega_{k,0}a^{-2} + \Omega_{\Lambda,0}\right)$$

$$\rho \propto a^{-3(1+\omega)}$$

Componente	ω	ρ
Materia	0	a^{-3}
Radiación	$1/3$	a^{-4}
Λ	-1	a^0

Introduction



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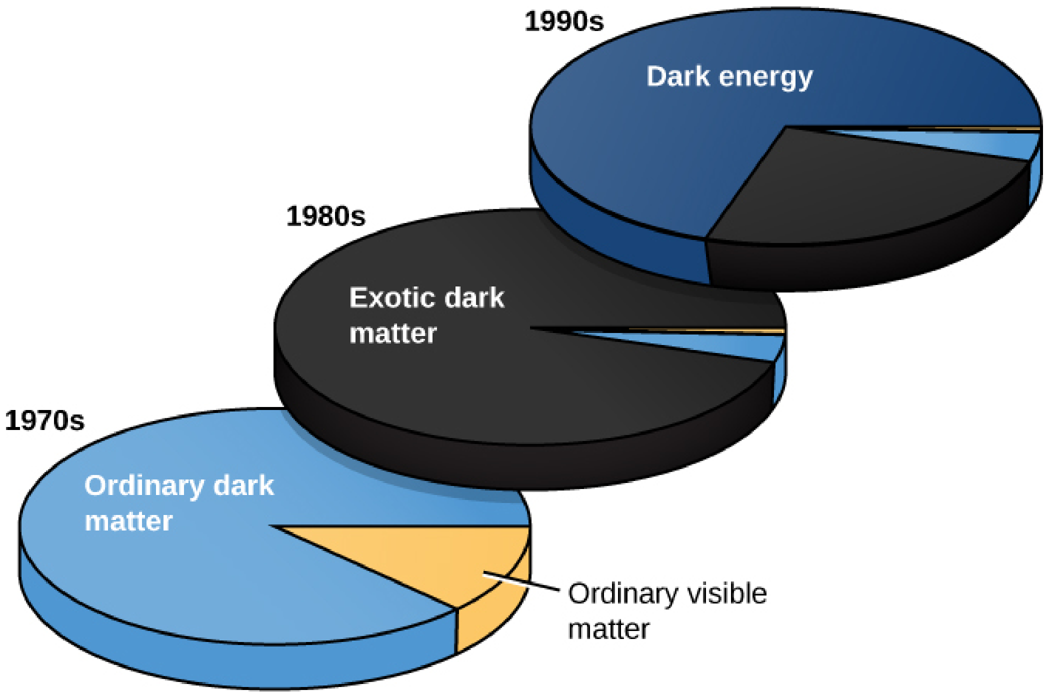
$$\begin{aligned} \omega &= -0.980 \pm 0.053 \\ H_0 &= (67.74 \pm 0.46)\text{km/s/Mp} \\ \Omega_m &= 0.3089 \pm 0.0062 \\ \Omega_k &= 0,000 \pm 0,005 \\ \Omega_\Lambda &= 0.6911 \pm 0.0062 \end{aligned}$$

Planck 2015 results. XIII. Cosmological parameters

Introduction



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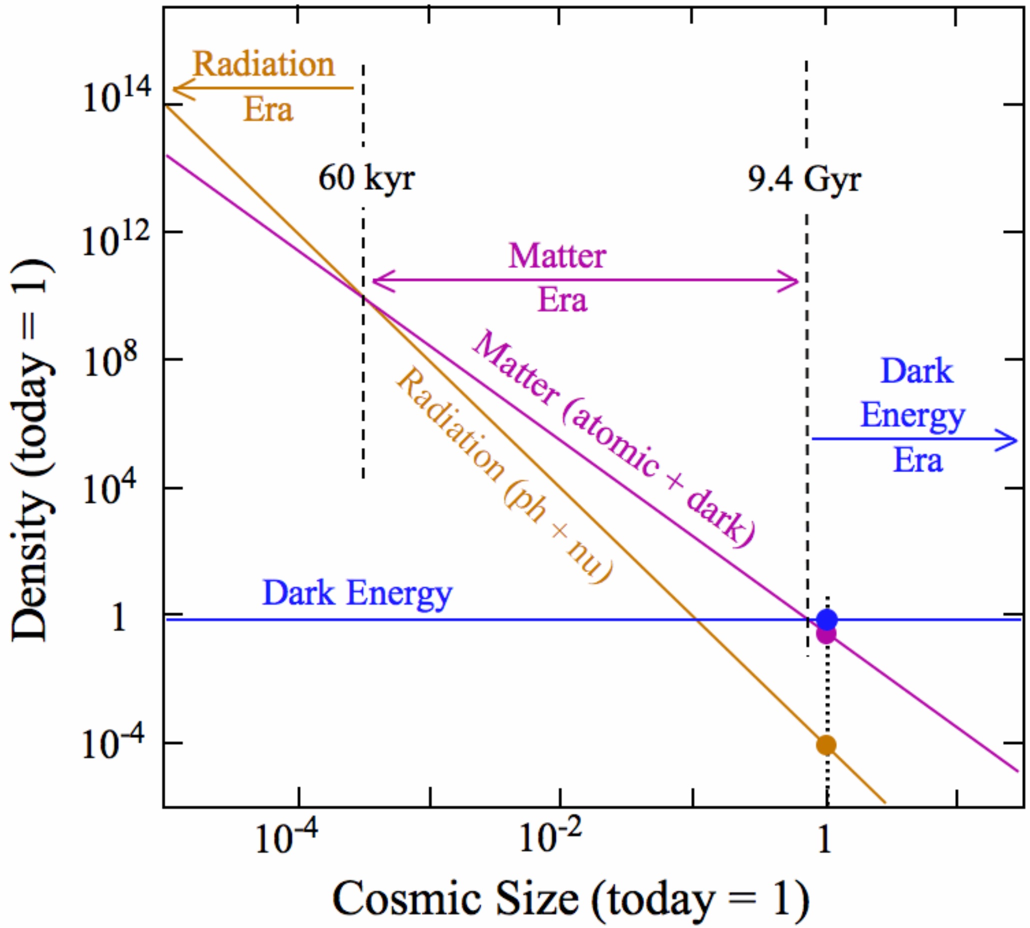


Alternative models

A great number of theoretical models of dark energy consider interactions with dark matter (solve the problem of coincidence). These models can be classified as phantom if EoS $\omega < -1$, or as quintessence if $\omega > -1$. In order to explain the current observations, the fine-tuning problem of the value of Λ and the cosmic coincidence problem, different alternative models have been proposed:

Model	Abbrev	Main feature	Θ_i
Lambda Cold Dark Matter	ΛCDM	$\omega = -1$	Ω_m, Ω_Λ
omega Cold Dark Matter	ωCDM	$\omega \neq -1$	Ω_m, ω
Chevallier-Polarski-Linder	CPL	$\omega(z)$	Ω_m, ω_0, ω_1
Interacting Dark Energy	IDE	Interaction DM/DE	Ω_m, δ, ω_x
Davali-Gabadadze-Porrati	DPG	Modified gravity	Ω_m
Early Dark Energy	EDE	Tracking field DE	Ω_m, Ω_e, ω_0

Tests

Among all these models we need to discriminate which one is the most favored by the current observations.

- **Geometrical test**: comparing models from observations of SNIa, CMB, BAO. It determine H(z) directly through the redshift dependence with cosmological distances (e.g. angular diameter distance $d_A(z)$, the volume-averaged distance $D_V(z)$ and mass gas fraction f_{gas}).
- **Dynamical test**: determine H(z) measuring the evolution of the density of matter-energy (background or perturbations) and they are connected with geometry through a theory of gravity. Linear growth factor of the matter density perturbations D(a).

Tests

We use the most recent observational data from CMB (Plank13+WMAP9) and LSS (SDSS, WiggleZ, 6dFGS, 2dFGRS) to put constraints on free parameters of the cosmological models in the previous section.

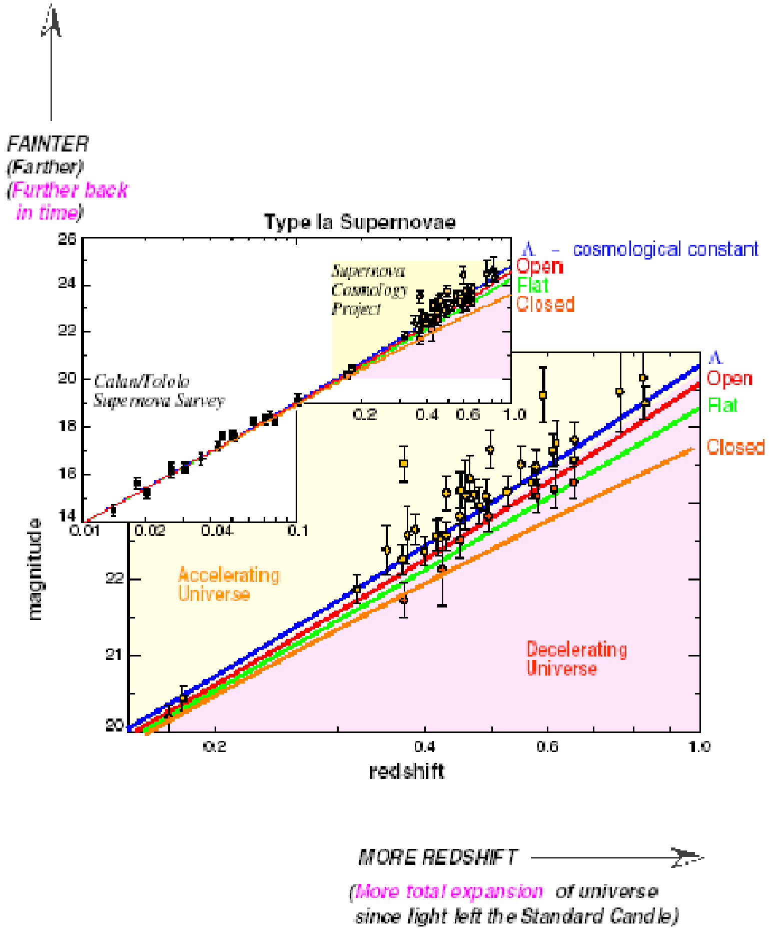
- CMB by using Shift parameter R

$$R = \frac{\sqrt{\Omega_m}}{c(1+z_*)} D_L(z) = \frac{l_1'^{TT}}{l_1^{TT}}. \tag{1}$$

- BAO by means of Distance Ratio Scale $D_v(z)/r_s$
- growth of LSS through Redshift-Space Distortions $A(z) = f(z)\sigma_8(z)$

$$\ddot{D}(a) + \left(\frac{3}{a} + \frac{\dot{H}}{H}\right)\dot{D}(a) - \frac{3}{2}\frac{\Omega_m}{a^5 H^2} f(a) D(a) = 0 \tag{2}$$

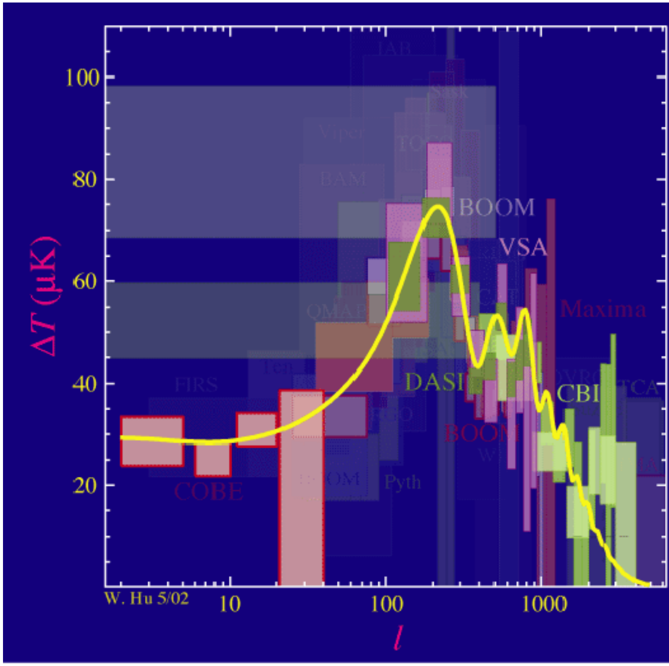
Tests



- $d_L(z)$ measurements, made using type Ia SNe, provide spectacular Hubble diagrams
- These indicate an expansion rate increasing with time
- Shorthand: consistent with $\tilde{0}.7$

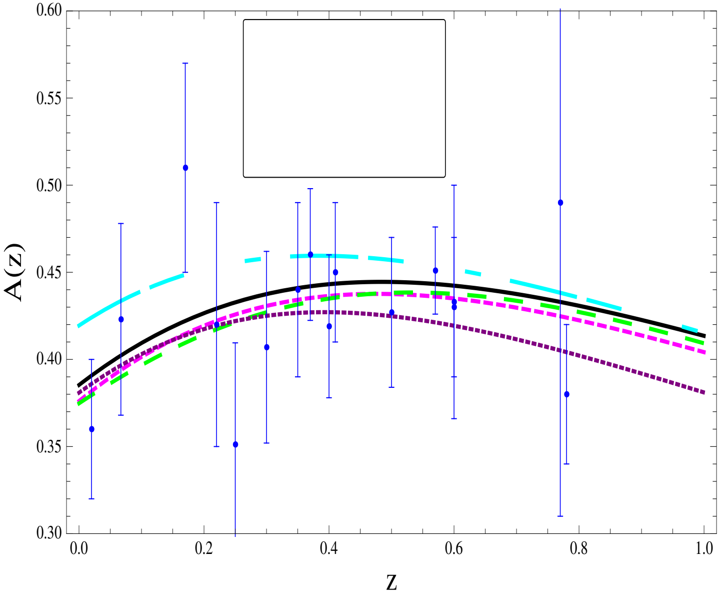
Tests

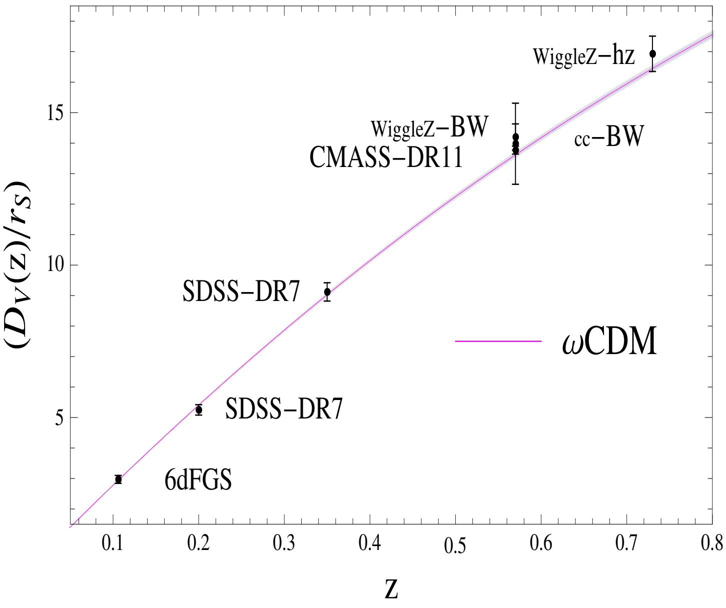
- Measurements of the first CMBR Doppler peak find total=1
- Many measurements of clusters, baryon fractions, etc. find matter 0.3
- Combined, these independently suggest the existence of dark energy



Wayne Hu: CMB data as of 5/02

- Maximum likelihood $\mathcal{L}_{max}$ and confidence level σ_i.
- Fisher matrix, error propagation and uncertainties.





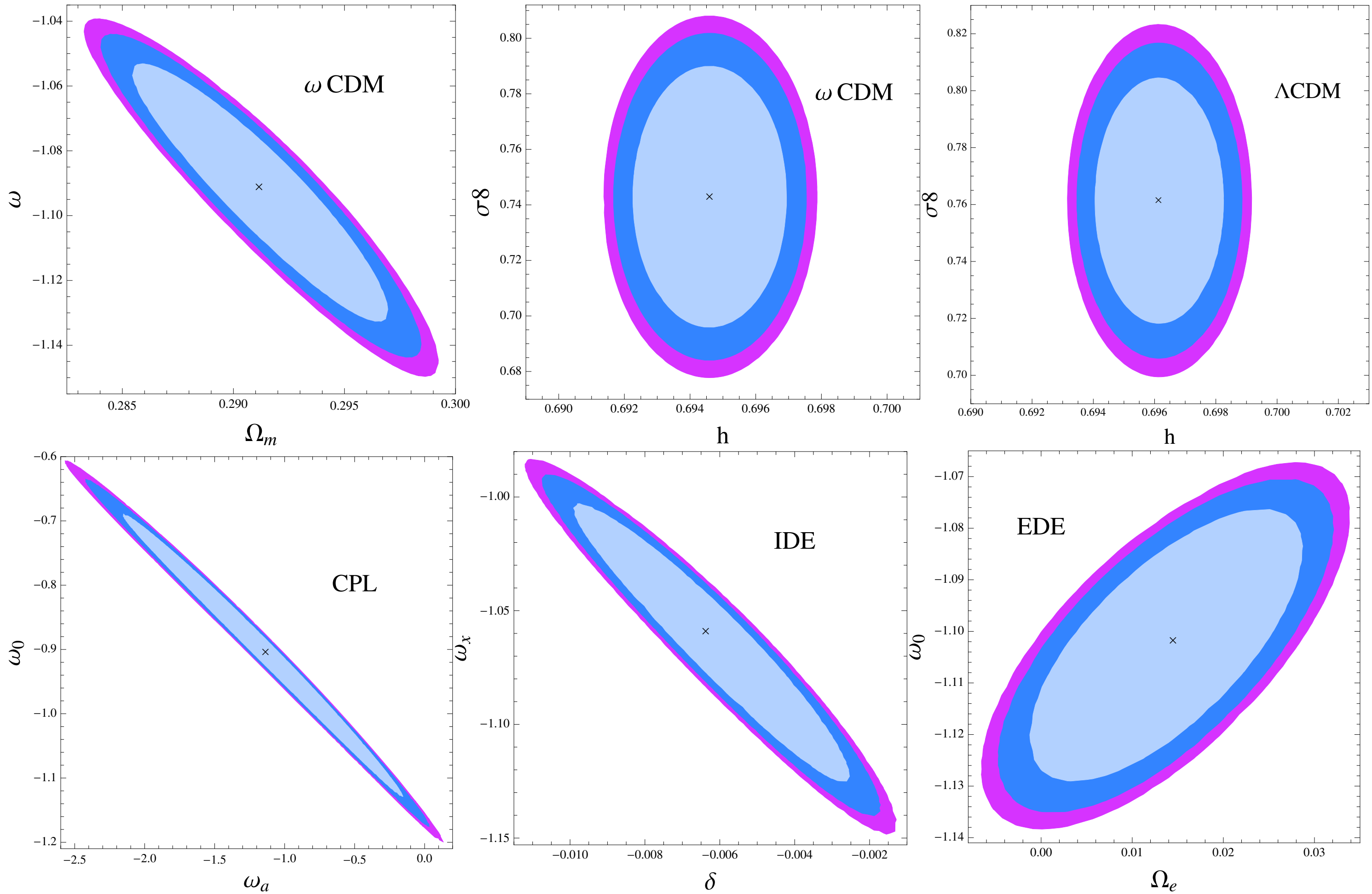


Figure 1: Diagrams of statistical confidence, marginalizing different

Results

Λ *Cold Dark Matter model*	
h=0.6969 $\pm$ 0.0016	σ_8=0.757 $\pm$ 0.019
Ω_m=0.2929 $\pm$ 0.0028	Ω_k=0.0022 $\pm$ 0.0008

Table 1: Best fit parameters Θ_i with all data set to ΛCDM model.

Model	**Parameter Vector** Θ_i
ΛCDM	$h = 0.711$, $\Omega_m = 0.2809^{+0.0091}_{-0.0097}$, $\Omega_\Lambda = 0.713^{+0.012}_{-0.013}$, $\Omega_b = 0.043$, $\sigma_8 = 0.780$
ωCDM	$h = 0.708$, $\Omega_m = 0.2837^{+0.0087}_{-0.0096}$, $\Omega_k = 0.002$, $\omega = -1.052^{+0.057}_{-0.068}$, $\Omega_b = 0.043$, $\sigma_8 = 0.755$
CPL	$h = 0.706$, $\Omega_m = 0.286$, $\Omega_k = -0.001$, $\omega_1 = -0.801$, $\omega_0 = -0.926$, $\Omega_b = 0.044$, $\sigma_8 = 0.748$
IDE	$h = 0.696$, $\Omega_m = 0.324$, $\Omega_k = 0.004$, $\delta = -0.007$, $\Omega_x = -1.083$, $\Omega_b = 0.044$, $\sigma_8 = 0.708$
EDE	$h = 0.692$, $\Omega_m = 0.319$, $\Omega_k = 0.014$, $\Omega_e = 0.012$, $\omega_0 = -0.967$, $\Omega_b = 0.044$, $\sigma_8 = 0.791$

Results

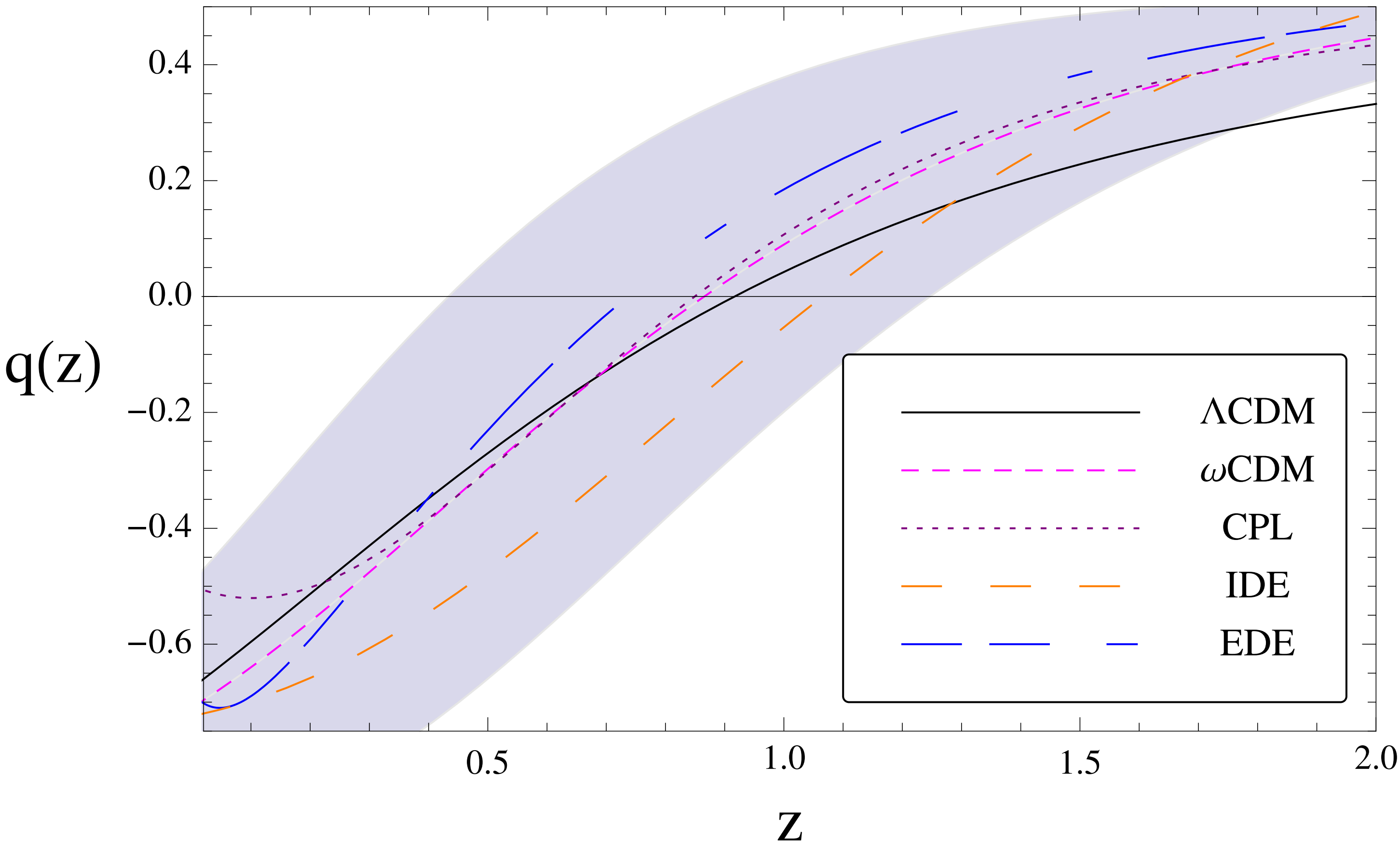
Par	ΛCDM	ωCDM	CPL	IDE
H_0	69.58 ± 0.22	69.46 ± 0.21	69.53 ± 0.22	68.73 ± 0.28
t_0	14.064 ± 0.044	14.087 ± 0.042	14.073 ± 0.045	14.236 ± 0.059
Ω_{r_0}	$8.613 \pm 0.054 \times 10^{-5}$	$8.651 \pm 0.053 \times 10^{-5}$	$8.634 \pm 0.056 \times 10^{-5}$	$8.835 \pm 0.073 \times 10^{-}$
Ω_{γ_0}	$5.100 \pm 0.032 \times 10^{-5}$	$5.118 \pm 0.031 \times 10^{-5}$	$5.108 \pm 0.33 \times 10^{-5}$	$5.226 \pm 0.43 \times 10^{-}$
Ω_{ν_0}	$3.521 \pm 0.022 \times 10^{-5}$	$3.533 \pm 0.021 \times 10^{-5}$	$3.526 \pm 0.022 \times 10^{-5}$	$3.608 \pm 0.029 \times 10^{-}$
ω_{m_0}	0.14007 ± 0.00088	0.14047 ± 0.00085	0.14005 ± 0.00091	0.1547 ± 0.0013
ω_{b_0}	0.02178 ± 0.00014	0.02171 ± 0.00013	0.02175 ± 0.00014	0.02129 ± 0.00017
Ω_{X_0}	0.7095 ± 0.0054	0.7126 ± 0.0053	0.7182 ± 0.0063	0.6693 ± 0.0061
ρ_{cri_0}	$9.101 \pm 0.057 \times 10^{-30}$	$9.070 \pm 0.055 \times 10^{-30}$	$9.088 \pm 0.058 \times 10^{-30}$	$8.881 \pm 0.073 \times 10^{-}$
ρ_{X_0}	$6.457 \pm 0.041 \times 10^{-30}$	$6.463 \pm 0.039 \times 10^{-30}$	$6.527 \pm 0.042 \times 10^{-30}$	$5.944 \pm 0.049 \times 10^{-}$
c_s	0.44965 ± 0.00056	0.44994 ± 0.00053	0.44977 ± 0.00057	0.45179 ± 0.00073
z_{drag}	1019.15 ± 0.39	1019.02 ± 0.37	1019.08 ± 0.39	1019.11 ± 0.49
r_{drag}	152.09 ± 0.42	152.04 ± 0.38	152.13 ± 0.41	146.78 ± 0.88
z_{cmb}	1092.52 ± 0.13	1092.66 ± 0.12	1092.56 ± 0.13	1094.61 ± 0.17

Table 2: Derived parameters for different cosmological dark energy models. We assume $\Omega_{b_0} = 0.045$ and $N_{eff} = 3.04$ for all cosmological models.

Model	k	χ^2_{min}	χ^2_{red}	AIC	ΔAIC	BIC	ΔBIC
CPL	6	808.856	1.109	822.738	2.88	850.353	7.48
Λ CDM	4	822.945	1.121	829.812	9.95	848.222	5.35
ω CDM	5	876.633	1.106	819.860	0.00	842.872	0.00
IDE	6	871.719	1.216	900.975	81.12	928.591	85.72
EDE	6	877.968	1.221	905.022	85.16	932.637	89.801

Table 3: Comparison of the different cosmological models with the ΔAIC y ΔBIC criterions using all complementary tests $(d_{A,c} + f_{gas} + BAO + CMB + SNIa + SL)$. The ωCDM model is the most favored model by these criterios.

Results



Conclusions

- Our analysis shows that ΛCDM ($\Omega_\Lambda = 0.713^{+0.012}_{-0.013}$, $\Omega_m = 0.2809^{+0.0091}_{-0.0097}$) dark energy model is preferred by ΔAIC and ΔBIC.
- The CPL, IDE and EDE model shows a anomalous behavior at low red-shift with BAO test, which may be telling us something about the local universe.
- This anomalous behavior is present only in models with dark energy density varying with the time.
- We compare this inflexion points (acelerate to slowdown) with the SDSS DR7 data, where we see that correspond with the actuallity acept homogenously scale ($\sim 150 Mpc$, $z \sim 0.2$).

References

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Any comment, collaboration or some interest, please contact us `joegarciafa@unal.edu.co`.

Thanks!