Model selection and constraints from Holographic dark energy models

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Holographic DE models: Theoretical proposal for DE scenarios

Holographic Principle

Holographic principle: based on the BH thermodynamics Gerard Hooft proposed the HP stating that all of the information contained in a volume of space can be represented as a hologram, which corresponds to a theory locating on the boundary of that space. Now it is widely believed that the HP should be a fundamental principle of quantum gravity.

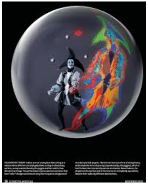


Figure: AdS/CFT

Holographic DE

In 2004, by applying the HP in cosmological scale, Miao Li proposed a new DE model the so-called Holographic DE. In this model, the energy density of DE depends on two physical quantity at the boundary of the universe: the reduced Planck mass M_p and the cosmological length scale L.

$$\rho_{de} = 3n^2 M_p^2 L^{-2} \tag{1}$$

Holographic DE models

Different Types of HDE models

(i)- Hubble Horizon length scale $L = H^{-1}$:
In this case we reach the wrong equation of State for DE.
(ii)- Particle Horizon length scale: In this case we cannot produce the accelerating Universe.
(iii)- Event Horizon (Model 1): Here the late time acceleration can be achieved successfully.

$$L = R_h = a \int_t^{\infty} \frac{dt}{a(t)} \tag{2}$$

Different Types of HDE models

(iv) - Ricci Scale length scale (Model 2): The late time acceleration and coincidence problem have been alleviated (Nojiri & Odintsov 2006).

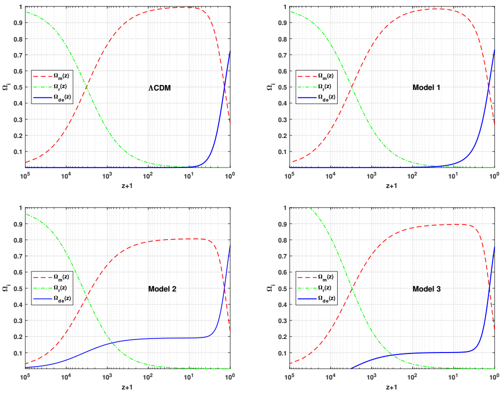
$$\rho_{de} = \frac{3\kappa}{8\pi}(\dot{H} + H^2) \tag{3}$$

(v) - Granda & Oliveros (GO) length scale (Model 3) (Granda & Oliveros,2008)

$$\rho_{de} = 3(\beta \dot{H} + \alpha H^2) \tag{4}$$

Evolution of HDE cosmologies

Background Evolution



HDE MODELS AGAINST OBSERVATION

EXPANSION DATA

The data used in this analysis: 1- 570 SNIa data from Union 2.1 (Suzuki et al. 2012)
2- 37 Hubble data H(z) Moresco et al. 2016
3- 6 distinct data from BAO measurements Anderson et al 2013
4- CMB data from WMAP experiments Shafer & Huterer, 2014
5- Big Bang Nucleosynthesis (BBN) Serra et al. 2009

METHOD USED IN THIS ANALYSIS

Standard χ^2 minimization based on the statistical MCMC algorithm.
AIC and BIC criteria: for comparison between different models with different numbers of free parameters.

FREE PARAMETERS OF MODELS

Standard LCDM mdoels: Ω_b, Ω_{dm}, H_0.
Model (1): Ω_b, Ω_{dm}, H_0 , n.
Model (2): Ω_b, Ω_{dm}, H_0.
Model (3): Ω_b, Ω_{dm}, H_0, β.

Numerical Results

Results of statistical likelihood analysis using different sets of background data for various HDE models and standard ΛCDM universe.

Model	Model (1)	Model (2)	Model (3)	ΛCDM
k	4	3	4	3
χ^2_{min}(total)	591.28	728.52	657.56	587.64
χ^2_{best}(SNIa)	562.43	600.53	609.09	562.23
χ^2_{best}(Hubble)	22.04	48.17	28.85	20.63
χ^2_{best}(BBN)	0.18	3.84	0.68	0.02
χ^2_{best}(CMB: WMAP data)	2.25	50.98	6.66	0.59
χ^2_{best}(BAO)	4.37	25.00	12.29	4.17
AIC	599.28	734.52	665.56	593.64
BIC	616.04	747.84	683.32	606.96

NUMERICAL RESULTS

BEST-FIT PARAMETERS FOR THE VARIOUS HDE MODELS USING THE COSMOLOGICAL DATA AT BACKGROUND LEVEL.

Model	Model(1)	Model(2)	Model(3)
$\Omega_{\rm m}$	$0.2677^{+0.0082,+0.016}_{-0.0082,-0.016}$	$\Omega_m = 0.2344^{+0.0070,+0.014}_{-0.0070,-0.013}$	$0.2438^{+0.0075,+0.015}_{-0.0075,-0.014}$
H_0	$69.29^{+0.92,+1.80,+2.30}_{-0.92,-1.80,-2.40}$	$75.20^{+0.79,+1.50,+2.00}_{-0.79,-1.50,-2.10}$	$71.66^{+0.90,+1.80,2.40}_{-0.90,-1.70,-2.30}$
n	$0.785^{+0.042,+0.10}_{-0.056,-0.094}$	–	–
β	–	–	$0.4369^{+0.0090,+0.017}_{-0.0090,-0.016}$
$w_{\rm de}(z=0)$	-1.10	-1.29	-1.32
$\Omega_{\rm de}(z=0)$	0.71372	0.77314	0.75447

LCDM

$\Omega_m = 0.2767^{+0.0083,+0.017,+0.022}_{-0.0083,-0.016,-0.021}$

$H_0 = 69.74^{+0.77,-1.50,-1.90}_{-0.77,+1.50,+1.90}$

$\Omega_{\rm de}(z=0) = 0.72627$

HDE MODELS IN PERTURBATION LEVEL

THE BASIC EQUATION FOR THE GROWTH OF PERTURBATIONS IN HDE COSMOLOGY

$$\delta_{\rm m}'' + \frac{3}{2a}(1 - w_{\rm d}\Omega_{\rm d})\delta_{\rm m}' = \frac{3}{2a^2}[\Omega_{\rm m}\delta_{\rm m} + \Omega_{\rm d}(1 + 3c_{\rm eff}^2)\delta_{\rm d}] \ , \tag{5}$$

$$\delta_{\rm d}'' + A\delta_{\rm d}' + B\delta_{\rm d} = \frac{3}{2a^2}(1 + w_{\rm d})[\Omega_{\rm m}\delta_{\rm m} + \Omega_{\rm d}(1 + 3c_{\rm eff}^2)\delta_{\rm d}] \ . \tag{6}$$

$$\begin{aligned} A &= \frac{1}{a}[-3w_{\rm d} - \frac{aw_{\rm d}'}{1 + w_{\rm d}} + \frac{3}{2}(1 - w_{\rm d}\Omega_{\rm d})], \\ B &= \frac{1}{a^2}[-aw_{\rm d}' + \frac{aw_{\rm d}'w_{\rm d}}{1 + w_{\rm d}} - \frac{1}{2}w_{\rm d}(1 - 3w_{\rm d}\Omega_{\rm d})]. \end{aligned} \tag{7}$$

Initial conditions (Batista & Pace 2013)

$$\begin{aligned} \delta_{\rm mi}' &= \frac{\delta_{\rm mi}}{a_{\rm i}} \ , \\ \delta_{\rm di} &= \frac{1 + w_{\rm di}}{1 - 3w_{\rm di}}\delta_{\rm mi} \ , \\ \delta_{\rm di}' &= \frac{4w_{\rm di}'}{(1 - 3w_{\rm di})^2}\delta_{\rm mi} + \frac{1 + w_{\rm di}}{1 - 3w_{\rm di}}\delta_{\rm mi}' \ , \end{aligned} \tag{8}$$

From above equations we calculate the $f(z)\sigma_8(z)$ quantity in HDE cosmologies.

Numerical Results

Numerical results for different homogeneous HDE models (part A) and clustered HDE models (part B) using the growth rate data. The results for concordance ΛCDM universe are shown for comparison.

Part (A)	Model 1 (homogeneous)	Model 2 (homogeneous)	Model 3 (homogeneous)
$\chi^2_{\rm min}(gr)$	11.2	11.9	11.1
AIC (BIC)	19.2 (19.6)	17.9 (18.8)	19.1 (19.5)
$\Omega_{\rm m}$	$0.242^{+0.055,+0.13,+0.20}_{-0.070,-0.12,-0.14}$	$0.277^{+0.061,+0.14,+0.20}_{-0.077,-0.013,-0.016}$	$0.216^{+0.052,+0.14,+0.22}_{-0.083,-0.12,-0.14}$
σ_8	$0.844^{+0.080,+0.23,+0.35}_{-0.12,-0.20,-0.22}$	$0.872^{+0.089,+0.21,+0.26}_{-0.11,-0.18,-0.20}$	$1.27^{+0.24,+0.78,+0.87}_{-0.48,-0.54,-0.57}$
Part (B)	Model 1 (clustered)	Model 2 (clustered)	Model 3 (clustered)
$\chi^2_{\rm min}(gr)$	11.2	12.0	11.1
AIC (BIC)	19.2(19.6)	18.0 (18.9)	19.1 (19.6)
$\Omega_{\rm m}$	$0.198^{+0.046,+0.10,+0.15}_{-0.054,-0.096,-0.12}$	$0.285^{+0.048,+0.12,+0.18}_{-0.065,-0.11,-0.13}$	$0.212^{+0.034,+0.12,+0.15}_{-0.056-0.84,-0.094}$
σ_8	$0.873^{+0.064,+0.17,+0.22}_{-0.085,-0.15,-0.17}$	$0.858^{+0.074,+0.18,+0.26}_{-0.089,-0.16,-0.19}$	$1.25^{+0.32,+0.52,+0.64}_{-0.28,-0.51,-0.63}$

We have used 18 data points for growth rate quantity.

LCDM

$\chi^2_{min} = 11.5$- AIC= 17.5- BIC=18.4

$\Omega_m = 0.257^{+0.052,+0.13,+0.18}_{-0.07,-0.12,-0.13}$ - $\sigma_8 = 0.813^{+0.061,+0.16,+0.24}_{-0.087,-0.14,-0.16}$

Numerical Results

Results of statistical likelihood analysis using different sets of background data combined with growth rate data $f(z)\sigma_8(z)$ for various homogeneous and clustered HDE models. The standard ΛCDM universe is shown for comparison. Values inside the parenthesis belong to clustered HDE models.

Model	Model 1	Model 2	Model 3	ΛCDM
k	5	4	5	4
$\chi^2_{\rm min}${total}	599.61 (599.34)	739.90 (740.75)	687.15 (688.20)	596.08
AIC {total}	609.61 (609.34)	747.90 (748.75)	697.15 (798.20)	604.08
BIC {total}	630.96 (631.69)	765.78 (766.63)	719.50 (720.55)	621.96

Numerical Results

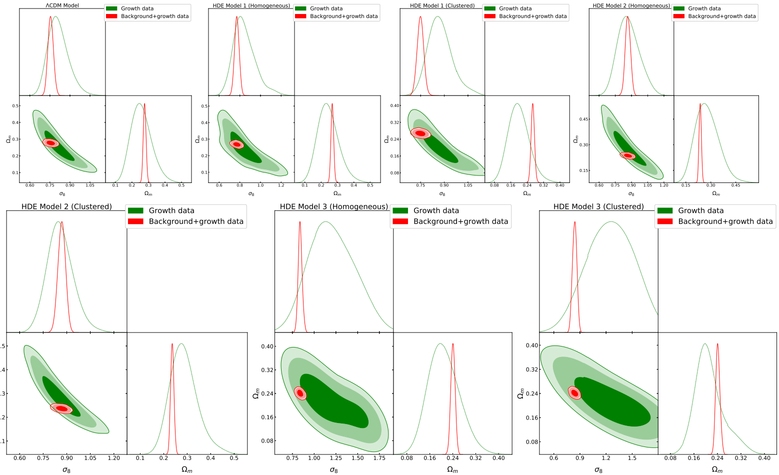


FIGURE: The 1σ, 2σ and 3σ likelihood contours in σ_8- Ω_m plane for different HDE models, including the concordance ΛCDM. The green contours correspond to the growth rate data, while the red contours obtained using the combination of expansion and growth data.

Concluding and Remarks

In this work we analyzed three popular types of holographic dark energy models using the latest observational data both in expansion and cluster scales. These observations include data from SNIa, BBN, BAO, Hubble expansion and the data from growth rate of structures.

While all three HDE models in perturbation level are well fitted to observation as equally as LCDM model, We showed that two out of the three HDE models i.e., holographic DE models based on Ricci scale and GO length scale disfavored by total cosmic observations.