Holographic dark energy: constraints on the interaction from observational data sets

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Expansion of the Universe and co-moving coordinate

- The Universe is **Expanding** (Hubble's observation, 1929).
- **Accelerated** expansion (*((Supernova Search Team), Riess A G et al., Astron. J.* **116***, 1009 (1998); Astron. J.* **117***, 707 (1999). (Supernova Cosmology Project) Perlmutter S et al., Astrophys. J.* **517***, 565 (1999).)*

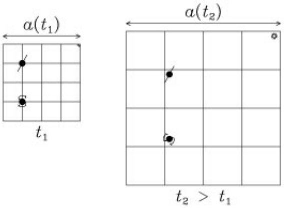

Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

Saul Perlmutter

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Friedmann Cosmology

The metric for a homogeneous and isotropic universe with spatially flat (k = 0) geometry:

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

Einstein's field equations ($G_{\mu\nu} = \kappa T_{\mu\nu}$) for this metric

$$3\frac{\dot{a}^2}{a^2} = 8\pi G\rho,$$

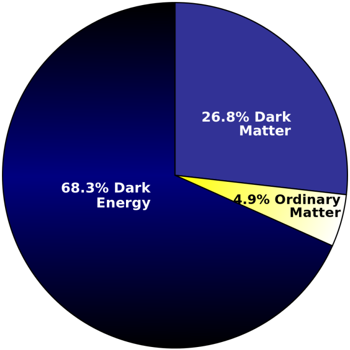
$$2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} = -8\pi Gp.$$

From Raychaudhuri equation,

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

Dark Energy

An exotic component introduced in the energy budget which can generate the cosmic acceleration by its characteristic negative pressure. It is dubbed as the **"Dark Energy"**.



Basic Holographic principle

- *"The phenomena within a volume can be explained by the set of degrees of freedom residing on its boundary and the d.o.f. are determined by the area of the boundary rather than the volume."* conjectured by 't Hooft and Susskind.
- Based on *the black hole entropy bound*, suggested by Bekenstein.
- The formation of a black hole leads to a connection between the *ultraviolet* (UV) cut-off, to the *infrared* (IR) cut-off by a constraint that "*the total quantum zero-point energy of the system should not exceed the mass of black holes of the same size.*"
- $L^3\rho_\Lambda \leq L{M_p}^2$, where ${M_p}^2 = (8\pi G)^{-1}$, ρ_Λ is the quantum zero-point energy density determined by the UV cut-off and L is the length scale of the system size.
- The inequality saturates in the IR cut-off limit.

Reconstruction of interaction term in holographic dark energy

- The holographic energy density is written as,

$$\rho_H = 3C^2 M_p^2 / L^2, \tag{1}$$

- The *Hubble horizon* assumed to be the IR cut-off, i.e. $L = \frac{1}{H}$.
- The Friedmann equations, in terms of Hubble parameters, are:

$$3H^2 = 8\pi G \rho_{tot}, \tag{2}$$

$$2\dot{H} + 3H^2 = -8\pi G p_{tot}, \tag{3}$$

where, ρ_{tot} and p_{tot} are respectively the energy density and pressure contributions of all the components in energy budget of the universe.

- The conservation equation of the total energy budget is

$$\dot{\rho}_{tot} + 3H(\rho_{tot} + p_{tot}) = 0. \tag{4}$$

where, $\rho_{tot} = \rho_m + \rho_{DE}$

- The conservation equation (equation (4)) can be separated into two parts,

$$\dot{\rho}_m + 3H\rho_m = Q, \tag{5}$$

$$\dot{\rho}_{DE} + 3H(1 + w_{DE})\rho_{DE} = -Q. \tag{6}$$

- This Q is the interaction term, and the w_{DE} is the dark energy equation of state parameter.
- The interaction term is assumed to be $Q = 3H\alpha(z)\rho_{DE}$, where the coupling term is α
- Coincidence parameter, $r = \rho_m/\rho_{DE}$
- If $\alpha = constant \implies H \propto (1+z)^{\frac{3}{2}(1-\frac{\alpha}{r})}$: *No transition from decelerated to accelerated phase of expansion*.

- A time varying $\alpha(z)$ is required for the successful transition.

Model I. $$\alpha(z) = \alpha_1 + \alpha_2(1+z) \quad (7)$$

Model II. $$\alpha(z) = \alpha_1 + \alpha_2\frac{z}{(1+z)} \quad (8)$$

Model III. $$\alpha(z) = \alpha_1 + \frac{\alpha_2}{(1+z)} \quad (9)$$

- The expressions of Hubble parameter obtained are;

I. $$H^2(z) = H_0^2\left[(1+z)^{3(1-\frac{\alpha_1}{r})}\exp\left(-3\frac{\alpha_2}{r}z\right)\right] \quad (10)$$

II. $$H^2(z) = H_0^2\left[(1+z)^{3(1-\frac{\alpha_1+\alpha_2}{r})}\exp\left(3\frac{\alpha_2}{r}\frac{z}{1+z}\right)\right] \quad (11)$$

III. $$H^2(z) = H_0^2\left[(1+z)^{3(1-\frac{\alpha_1}{r})}\exp\left(-3\frac{\alpha_2}{r}\frac{z}{1+z}\right)\right] \quad (12)$$

- Note that the DE and DM terms cannot be separately identified in the Hubble parameter expressions!
- The models cannot be reduced to non-interacting ones.
- If $\alpha_1 = \alpha_2 = 0 \implies$ pure CDM model.
- $r = 0.445 \pm 0.010$ estimated from the "*Planck* measurement" of Ω_Λ. [2]
- Parameters re-defined as: $\beta_1 = \dfrac{\alpha_1}{r}$, and $\beta_2 = \dfrac{\alpha_2}{r}$.
- Hubble constant, H_0 scaled by 100 $km.sec.^{-1}Mpc^{-1}$ and represented in a dimensionless way as h_0.
- The direction of energy flow in the interaction between DE and DM will be determined by the signatures of α_1, and α_2 .
- $Q = +ve \implies$ the energy flow from DE to DM, and vice-versa!

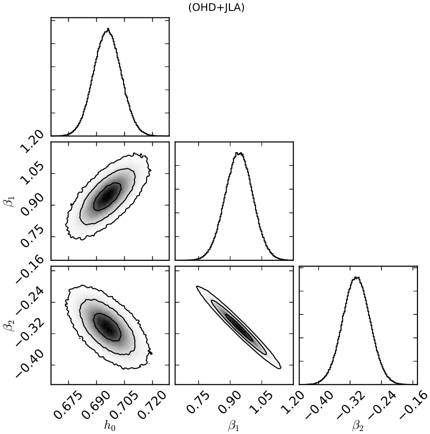
Observational Data

In the present analysis, the supernova distance modulus data (**SNe**), and observational measurements of Hubble parameter (**OHD**) data have been utilized to constrain the model parameters.

OHD (observational measurements of the Hubble parameter): *J. Simon, L. Verde and R. Jimenez, Phys. Rev. D* **71**, *123001 (2005); D. Stern, R. Jimenez, L. Verde, M. Kamionkowski and S.A. Stanford, JCAP 02(2010)008 ; M. Moresco et al., JCAP 07(2012)053 ; C. Zhang et al., Res. Astron. Astrophys.,* **14**, *1221 (2014); T. Delubac et al. Astron. Astrophys.* **574** *A59 (2015).*

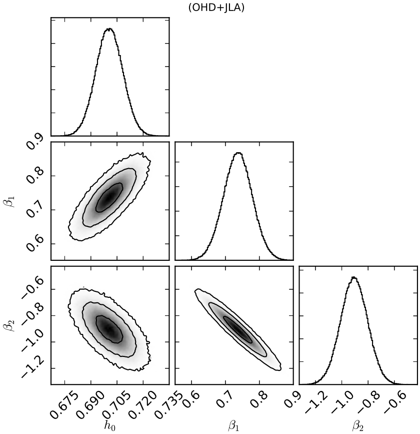
SNe (distance modulus data of type Ia supernova): *N. Suzuki et al., Astrophys. J.* **746**, *85 (2012); M. Betoule et al., Astron. Astrophys.* **568**, *A22 (2014).*

Model I : (OHD+JLA)



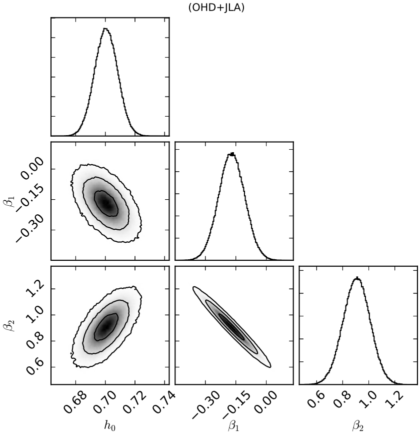
	h_0	β_1	β_2
OHD+JLA	$0.696^{+0.007}_{-0.007}$	$0.942^{+0.065}_{-0.066}$	$-0.304^{+0.035}_{-0.034}$

Model II : (OHD+JLA)



	h_0	β_1	β_2
OHD+JLA	$0.700^{+0.008}_{-0.008}$	$0.737^{+0.042}_{-0.042}$	$-0.906^{+0.102}_{-0.102}$

Model III : (OHD+JLA)



	h_0	β_1	β_2
OHD+JLA	$0.700^{+0.008}_{-0.008}$	$-0.170^{+0.064}_{-0.063}$	$0.907^{+0.102}_{-0.103}$

Reconstruction of the effective equation of state

The dark energy equation of state parameter w_{DE} is related to w_{eff} as,

$$w_{DE} = w_{eff}(1 + r). \quad (13)$$

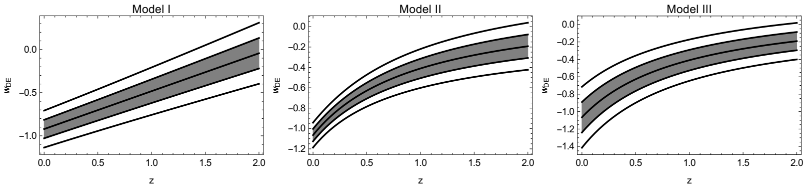


Figure: Plots of dark energy equation of state for the reconstructed models.

Evolution of the cosmological parameters

The rate of interaction between DE and DM, $\Gamma = Q/\rho_H = 3H(z)\alpha(z)$ [2, 3].

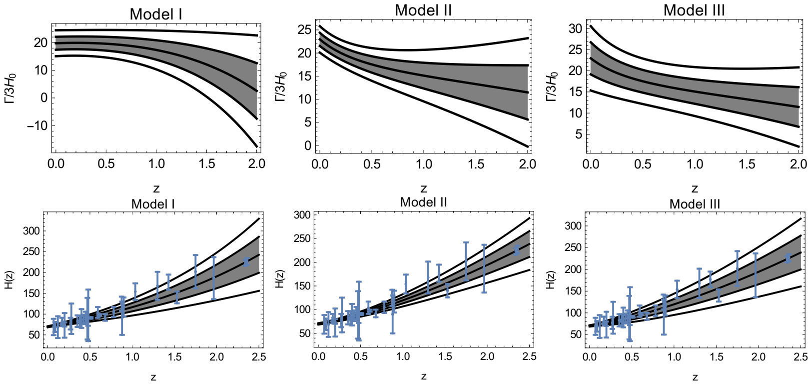


Figure: Plots of the interactions rate Γ scaled by $3H_0$ and the Hubble parameter $H(z)$ for the reconstructed models.

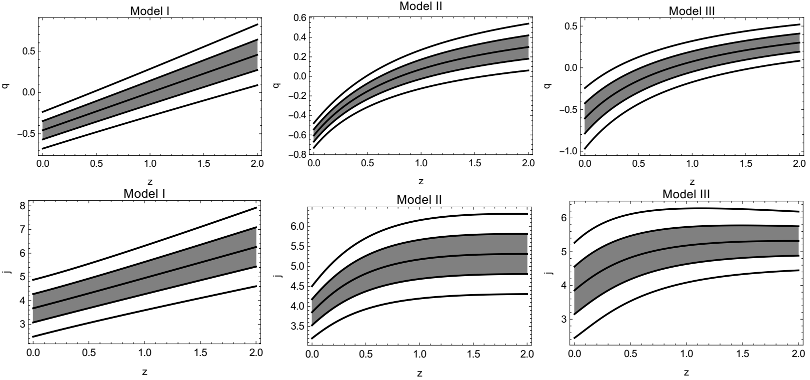


Figure: Plots of deceleration parameter (upper panels) and the cosmological jerk parameter (lower panels) for the reconstructed models.

Bayesian Evidence Calculation

- Statistical preference of a model is judged by calculation the Bayesian evidence.

$$E = \int (Prior \times Likelihood)\, d\theta_1\, d\theta_2 ....\, d\theta_n, \tag{14}$$

where θ_i's are the model parameters.

Model I. $$E_1 = P_1 \int Likelihood\, d\beta_1\, d\beta_2\, dh_0 = 9.823 \times 10^{-22}, \tag{15}$$

Model II. $$E_2 = P_2 \int Likelihood\, d\beta_1\, d\beta_2\, dh_0 = 4.123 \times 10^{-13}, \tag{16}$$

Model III. $$E_3 = P_3 \int Likelihood\, d\beta_1\, d\beta_2\, dh_0 = 4.726 \times 10^{-13}, \tag{17}$$

Summary and Conclusion

• Holographic dark energy model has been reconstructed for three different choices of the interaction term.

• The Hubble radius has been chosen as the IR cut-off.

• In the present analysis, the viable nature of the interaction rate is obtained.

• Results shows that $\alpha \approx (1+z)$ type of models (Model I) are not consistent with the observed evolution scenario. On the other hand, Model II and III are highly consistent with observed nature of the deceleration parameter (upper panel 3).

• Calculation of Bayesian evidence also shows that Model I is ruled out in comparison with Model II and Model III. The interaction is only significant at low redshift regime.

• The dark energy component is indistinguishable from dark matter component at high redshift. w_{DE} is small at high redshift for these models.

• The interaction term Q remains positive which indicates that the pumping of energy is from DE component to DM component (Q should be positive as a thermodynamic requirement, according to Pavon and Wang).

• The present value of $j(z)$ remains in between 3 to 5 at 1σ level which shows a strong departure from ΛCDM value of unity.

List of References

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THANK YOU