Tracker phantom field and a cosmological constant: dynamics of a composite dark energy model

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Introduction: The accelerated expansion of the universe is still a mystery as the cause of it remains unknown even after a decade of its discovery. Out of many explanations, introductions of a scalar field as a component of the universe is a popular choice. In this work, we study tracker phantom dark energy models with a general parameterization of the scalar potentials. Our analysis also considers the scenario of having both phantom field and the cosmological constant as the dark energy components. A detailed statistical analysis with current cosmological observations shows an increase in the value of the Hubble parameter due to the presence of phantom dark energy but it can not alleviate the Hubble tension completely. Our results using Bayesian methods suggests a decisive evidence in favor of a phantom field over a positive cosmological constant, although the possibility of a negative cosmological constant cannot be ruled out hidden in the dark sector.

$$H^2 = \frac{\kappa^2}{3}\left(\sum_j \rho_j + \rho_\phi\right), \quad \dot{\rho}_j = -3H(\rho_j + p_j)$$

$$\dot{H} = -\frac{\kappa^2}{2}\left[\sum_j (\rho_j + p_j) + (\rho_\phi + p_\phi)\right],$$

$$\ddot{\phi} = -3H\dot{\phi} + \partial_\phi V(\phi),$$

Field equations & wave equation

$$\theta' = -3\sinh\theta - y_1,$$

$$y_1' = \frac{3}{2}\gamma_{tot} y_1 + \Omega_\phi^{1/2}\sinh(\theta/2) y_2,$$

$$\Omega_\phi' = 3(\gamma_{tot} - \gamma_\phi)\Omega_\phi.$$

Dynamical System

$$\frac{\kappa\dot{\phi}}{\sqrt{6}H} \equiv \Omega_\phi^{1/2}\sinh(\theta/2) \qquad \frac{\kappa V^{1/2}}{\sqrt{3}H} \equiv \Omega_\phi^{1/2}\cosh(\theta/2)$$

$$y_1 \equiv -2\sqrt{2}\,\frac{\partial_\phi V^{1/2}}{H} \qquad y_2 \equiv -4\sqrt{3}\,\frac{\partial_\phi^2 V_\phi^{1/2}}{\kappa H}$$

Hyperbolic polar Transformation

General Parameterization of Potentials

$$y_2 = y\left(\alpha_0 + \alpha_1 y_1/y + \alpha_2 y_1^2/y^2\right)$$

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Tracking Condition

$$\gamma_{\phi,c} = -\gamma_{tot}/2\alpha_2$$

$$\cosh\theta_i = 1 + \frac{2}{3\alpha_2}, \quad y_{1i} = -3\sinh\theta_i,$$

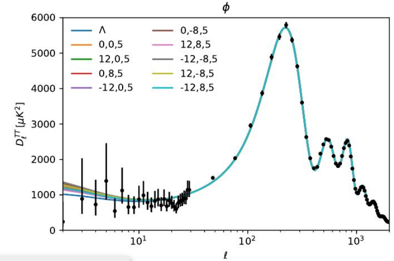
$$\Omega_{\phi i} = A \times a_i^{4(1+1/2\alpha_2)}\left(\frac{\Omega_{m0}}{\Omega_{r0}}\right)^{1+1/2\alpha_2}\Omega_{\phi 0}$$

A set of initial conditions has been obtained using the initial condition and the equations are introduced in an Boltzmann code class (v2.9).

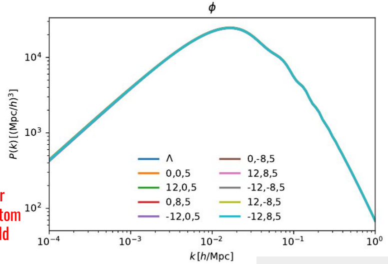
Linear Perturbation in Synchronous Gauge

$$\delta_0' = \left[-3\sinh\theta - \frac{k^2}{k_J^2}(1-\cosh\theta)\right]\delta_1 - \frac{k^2}{k_J^2}\sinh\theta\,\delta_0 - \frac{\bar{h}'}{2}(1-\cosh\theta),$$

$$\delta_1' = \left(-3\cosh\theta + \frac{k_{eff}^2}{k_J^2}\sinh\theta\right)\delta_1 - \frac{k_{eff}^2}{k_J^2}(1+\cosh\theta)\delta_0 + \frac{\bar{h}'}{2}\sinh\theta. \quad (7b)$$

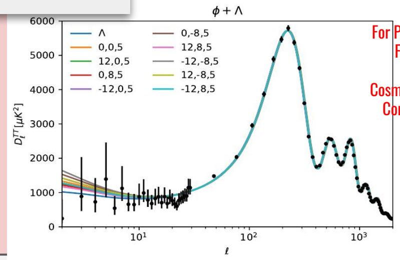


For Phantom Field

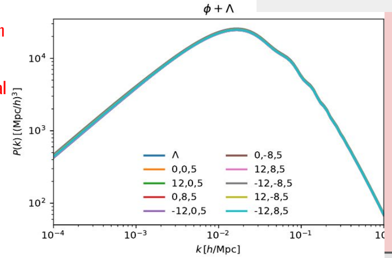


CMB anisotropies

Mass Power Spectrum



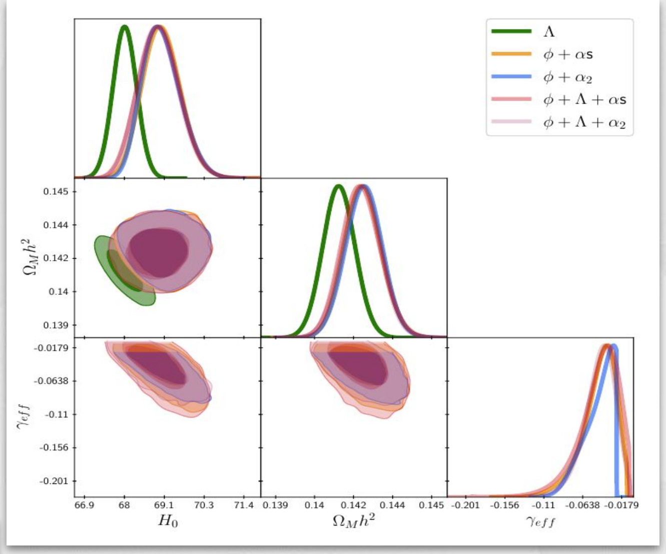
For Phantom Field + Cosmological Constant

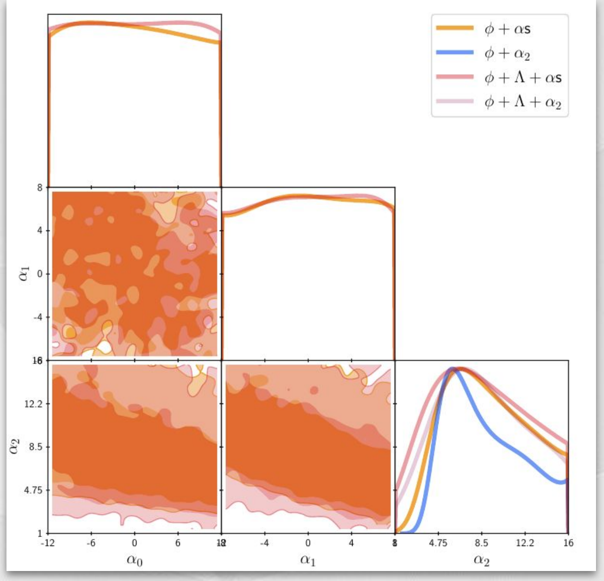


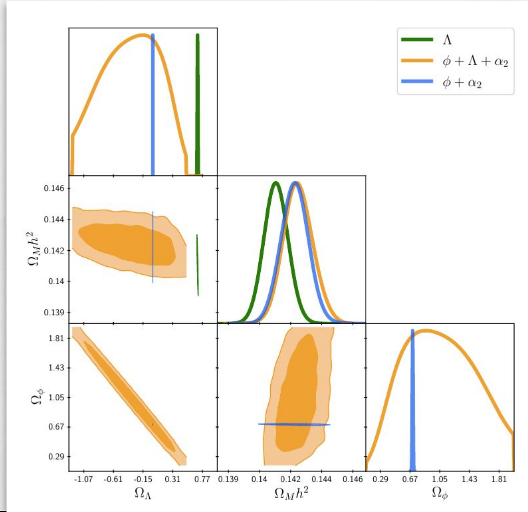
Observational Constraints

We have used the aforementioned Boltzmann code class and the MCMC sampler montepython (v3.3), together with the following observations: Pantheon, BAO (BOSS DR12, 6dFGS,, eBOSS DR14 (Lya), and WiggleZ , SHOES, SDSS LRG DR7, SDSS LRG DR4 and WiggleZ and a compressed Planck likelihood.

Three different models, cosmological constant (Λ), phantom DE (φ), and the phantom DE with cosmological constant (φ + Λ) has been studied for different combinations of the active parameters.







Parameter	Λ	$\phi+\alpha$'s	$\phi+\alpha_2$	$\phi+\Lambda+\alpha$'s	$\phi+\Lambda+\alpha_2$	$\phi+\Lambda+\alpha_2$ (Ext.)
H_0	$68.0^{+0.3}_{-0.3}$	$69.1^{+0.5}_{-0.6}$	$69.1^{+0.5}_{-0.6}$	$69.0^{+0.6}_{-0.6}$	$69.0^{+0.5}_{-0.6}$	$69.28^{+0.63}_{-0.62}$
$\Omega_M h^2$	$0.141^{+0.0007}_{-0.0007}$	$0.142^{+0.0008}_{-0.0009}$	$0.142^{+0.0008}_{-0.0008}$	$0.142^{+0.0008}_{-0.0009}$	$0.142^{+0.0008}_{-0.0008}$	$0.1426^{+0.00088}_{-0.0009}$
γ_{eff}	0	$-0.045^{+0.026}_{-0.012}$	$-0.045^{+0.024}_{-0.006}$	$-0.045^{+0.030}_{-0.014}$	$-0.044^{+0.022}_{-0.014}$	$-0.04792^{+0.017}_{-0.014}$
Ω_Λ	$0.694^{+0.0046}_{-0.0043}$	0	0	$0.0462^{+0.144}_{-0.317}$	$0.0371^{+0.133}_{-0.315}$	$-0.3504^{+0.56}_{-0.4}$
Ω_ϕ	0	$0.7013^{+0.0048}_{-0.0047}$	$0.7012^{+0.0046}_{-0.0051}$	$0.6249^{+0.37}_{-0.12}$	$0.9138^{+0.34}_{-0.56}$	$1.053^{+0.4}_{-0.56}$
α_2	0	$8.99^{+3.0}_{-4.7}$	$8.78^{+2.02}_{-4.68}$	$8.47^{+0.37}_{-0.12}$	$8.56^{+3.65}_{-4.51}$	$10.48^{+5.5}_{-1.7}$
k	0	+3	+1	+4	+2	+1
$\Delta\chi^2_{min}$	0	−6	−5	−5	−5	−4
$\ln B_{\phi\Lambda}$	0	+2.51 Definite/Positive	+2.13 Definite/Positive	+2.27 Definite/Positive	+2.05 Definite/Positive	+2.05 Definite/Positive

Conclusions

- We have studied the tracking behavior of the phantom dark energy models and analyzed its dynamics under a general parameterization of the phantom field potential.
- The sufficient and necessary condition for the phantom field to have a tracking behavior involves just one active parameter.
- Different class of solutions has been studied and we found that scaling solution does not exist for the phantom models.
- Although we find a noticeable shift of the central value of the Hubble parameter but it is not enough to solve the Hubble tension.
- We have done Bayesian model comparison for three different models, cosmological constant (Λ), phantom DE (φ), and the phantom DE with cosmological constant ($\varphi + \Lambda$).
- We found that data favor the existence of phantom DE over the positive cosmological constant.
- The main result is that a negative cosmological constant can not be ruled out while there is a phantom scalar field component.
- It will be interesting to investigate multicomponent DE models with at least one phantom scalar field.