Signature of dark energy/modified gravity in galaxy power spectrum on the large cosmological scale.

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Abstract

Dark energy cluster only on large scale and on large-scale extra general relativistic corrections are needed to observe galaxy power spectrum. The observed galaxy power spectrum enhances on large scale compared to the small scale due to these two extra effects. This effect also help us to distinguish different dark energy/modified models more efficiently on large scale compared to the small scale.

Introduction

The ΛCDM model is the simplest model of the dark energy. However it is worth investigating different evolving dark energy models. One of the best possible cosmological observable is the galaxy power spectrum through which we can see effect of dark energy. When we observe galaxy power spectrum, the general relativistic corrections are needed on large scale which enhances the observed galaxy power spectrum on large scale compared to the small scale. On the other hand the dark energy can cluster on large scale. Due to these extra effects, we can distinguish different dark energy models on large scales more effectively compared to the small scale.

1 Background evolution

We consider cubic Galileon action along with a potential [1]

$$S = \int d^4x\sqrt{-g}\Big[\frac{M_{\rm pl}^2}{2}R + \frac{1}{2}(\nabla\phi)^2\Big(1+\frac{\alpha}{M^3}\Box\phi\Big) - V(\phi)\Big] + \mathcal{S}_m\,, \tag{1}$$

where all the notations are standard.

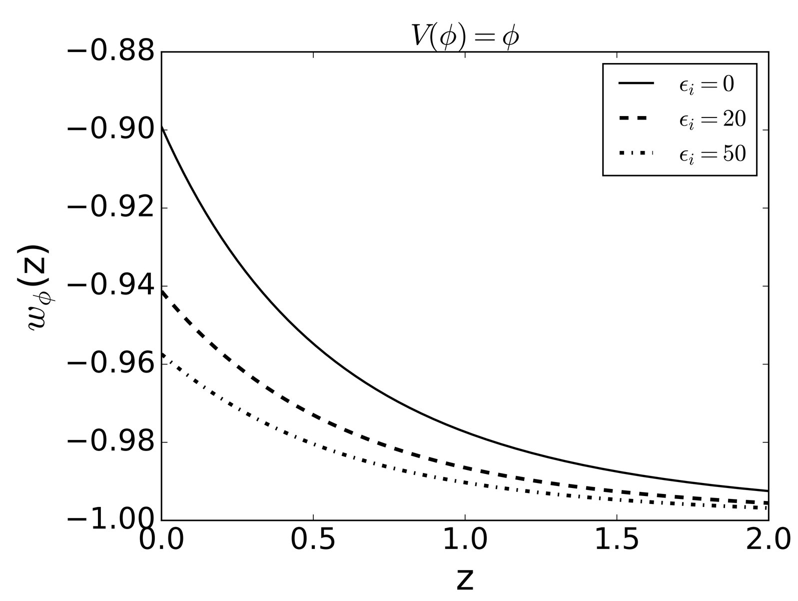

Figure 1: Behaviour of the e.o.s for the Galileon field with linear potential.

From Fig. 1, we can see that the deviation is the largest for $\epsilon_i = 0$ (which is the case of quintessence) and deviations decrease with increasing $\epsilon_i = 0$. Here ϵ is defined as $\epsilon = -6\beta H^2\Big(\frac{d\phi}{dN}\Big)$.

2 Relativistic perturbations

In the conformal Newtonian gauge the linearized Einstein equations become

$$\vec{\nabla}^2\Phi - 3a^2H(\dot\Phi + H\Phi) = 4\pi G a^2\sum_i \delta\rho_i\,, \qquad \dot\Phi + H\Phi = 4\pi G a\sum_i(\bar\rho_i + \bar P_i)v_i\,,$$
$$\ddot\Phi + 4H\dot\Phi + (2\dot H + 3H^2)\Phi = 4\pi G\sum_i \delta P_i,$$

where the summation is over matter and Galileon field. The first order perturbed energy density, pressure and velocity for the Galileon field ϕ are respectively given by [1]

$$\delta\rho_\phi = (1-9\beta H\dot\phi)\dot\phi\delta\dot\phi + \beta\dot\phi^2\frac{\vec\nabla^2\delta\phi}{a^2} - (1-12\beta H\dot\phi)\dot\phi^2\Phi + 3\beta\dot\phi^3\dot\Phi + V_\phi\delta\phi, \tag{2}$$
$$\delta P_\phi = \beta\dot\phi^2\delta\ddot\phi + (1+2\beta\ddot\phi)\dot\phi\delta\dot\phi - (1+4\beta\ddot\phi)\dot\phi^2\Phi - \beta\dot\phi^3\dot\Phi - V_\phi\delta\phi, \tag{3}$$
$$a(\bar\rho_\phi + \bar P_\phi)v_\phi = \dot\phi\Big[\beta\dot\phi\delta\dot\phi + (1-3\beta H\dot\phi)\delta\phi - \beta\dot\phi^2\Phi\Big], \tag{4}$$

We solve above differential equations to find the behaviour of the first order quantities (with first order Euler equation). We calculate comoving matter energy density contrast by using the definition $\Delta_m = \delta_m + 3\mathcal{H}v_m$.

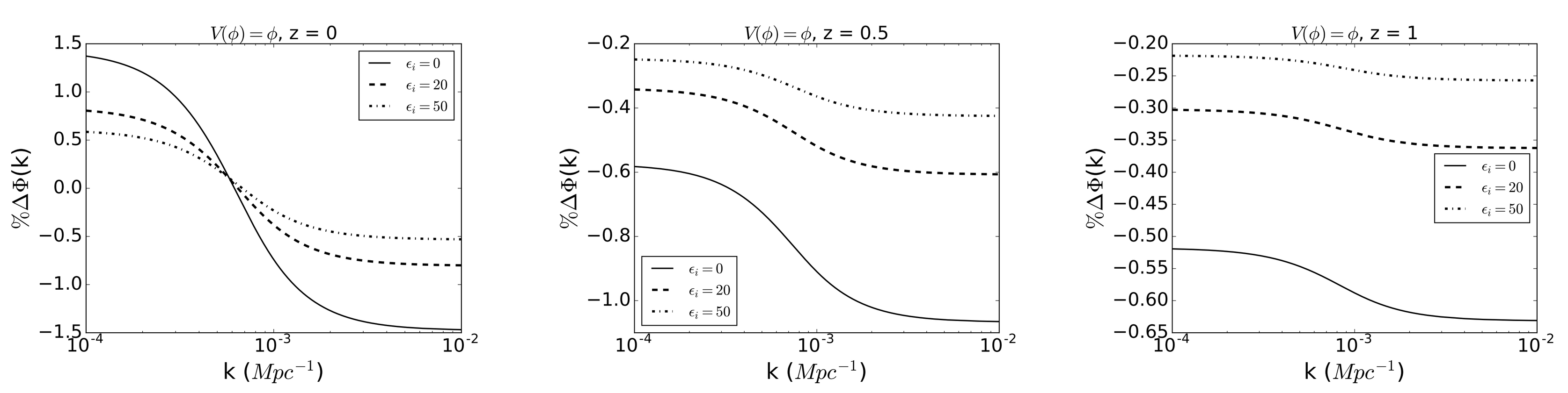

Figure 2: Percentage deviation in Φ from ΛCDM model for different ϵ_i with linear potential.

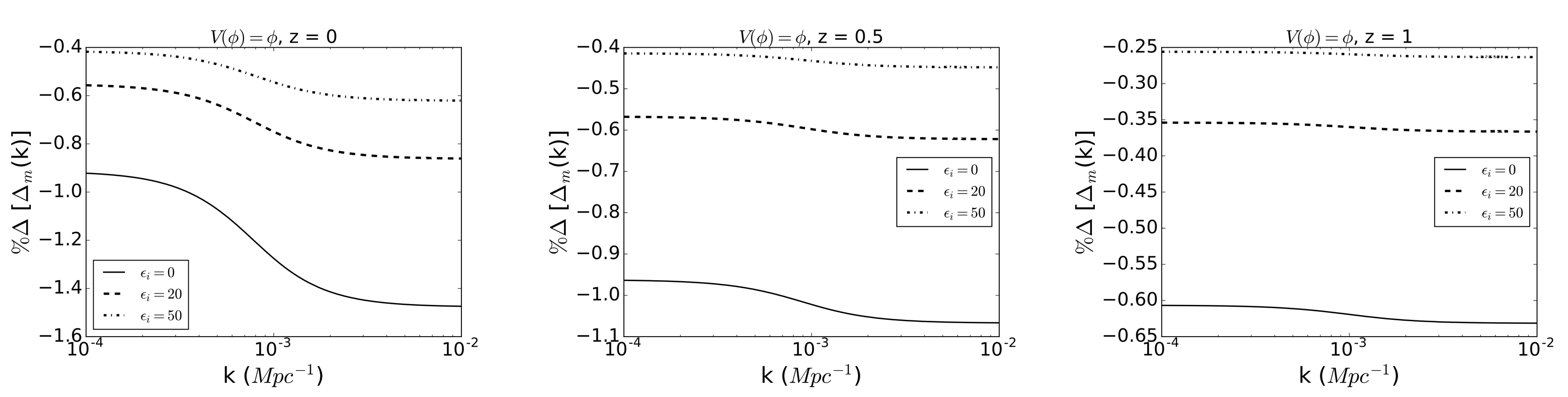

Figure 3: Percentage deviation in Δ_m from ΛCDM model for different ϵ_i with linear potential.

From Figs. 2 and 3, we can see that the deviations in two important perturbation variables, Φ and Δ_m enhance on large scale compared to the small scale due to the dark energy perturbations.

3 The observed galaxy power spectrum

The observed galaxy overdensity power spectrum $P_{\rm g}$ is given by [2, 3, 4]

$$P_{\rm g}(k,z) = \left[\left(b+f\mu^2\right)^2 + 2\left(b+f\mu^2\right)\left(\frac{\mathcal{A}}{Y^2}\right) + \frac{\mathcal{A}^2}{Y^4} + \mu^2\left(\frac{\mathcal{B}^2}{Y^2}\right)\right]P_{\rm m}(k,z)\,, \tag{5}$$

where last three terms are GR corrections and $P_{\rm m}$ is the matter power spectrum. The $\mathcal{A}$ term is related to the peculiar velocity field and the $\mathcal{B}$ term is related to the Doppler effect. In all the subsequent plots by $P_{\rm k}$ we mean $P_{\rm k}(k,z) = \left(b+f\mu^2\right)^2 P_{\rm m}(k,z)$. This is called Kaiser power spectrum which is basically observed galaxy power spectrum without GR corrections i.e. Newtonian counterpart of the observed galaxy power spectrum.

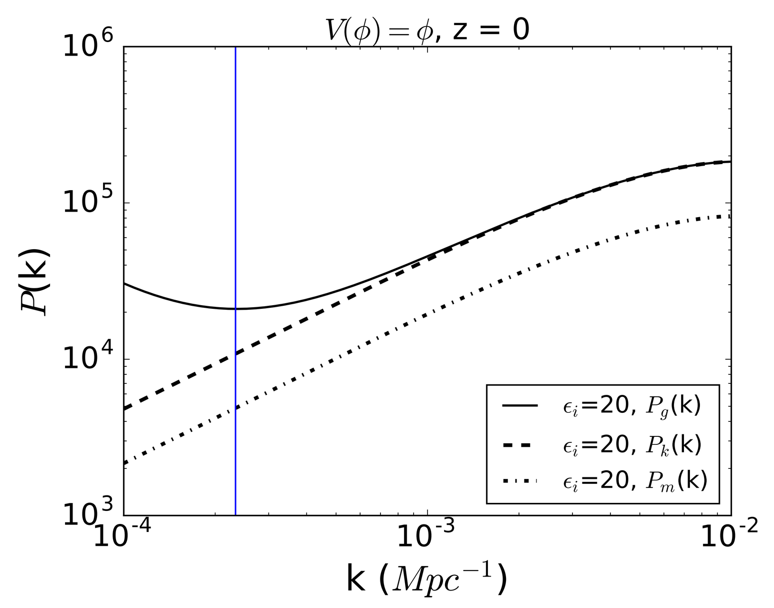

Figure 4: Dashed-dotted, dashed and continuous lines are for the $P_{\rm m}$, $P_{\rm k}$ and $P_{\rm g}$ respectively for $\epsilon_i = 20$. The vertical blue line is the horizon scales at $z = 0$. We see that the observed galaxy power spectrum (P_g) enhances from its Newtonian counterpart Kaiser power spectrum (P_k) on larger scales only due to the extra effect from the general relativistic corrections through $\mathcal{A}$ and the $\mathcal{B}$ terms in Eq. (5).

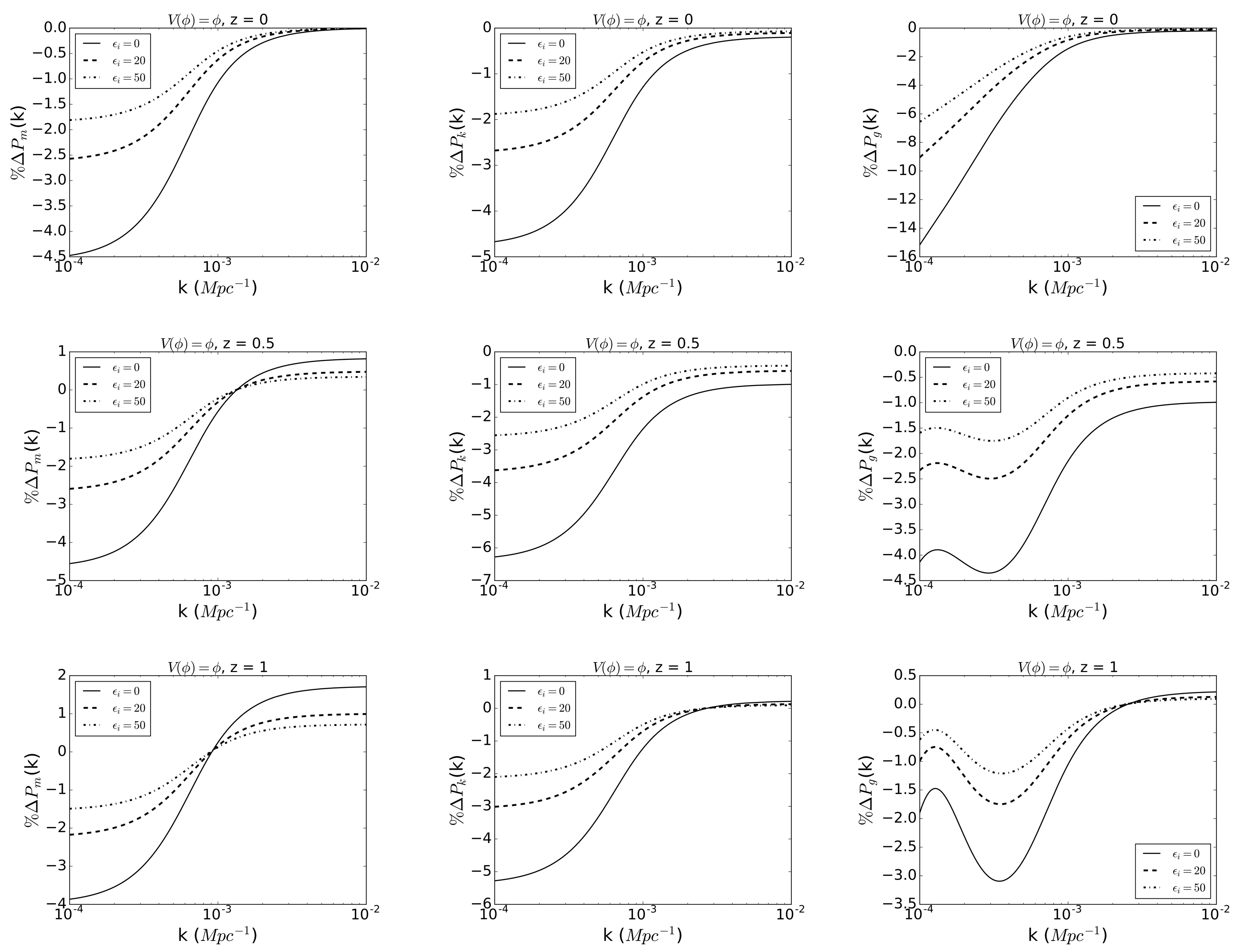

Figure 5: Percentage deviation in $P(\rm k)$ from ΛCDM model for different ϵ_i with linear potential as a function of k. We see that the deviations in the standard matter power spectrum (P_m) are larger on large scale compared to the small scale due to extra effect from dark energy perturbations. The similar happens to the Kaiser power spectrum (P_k) because from Fig. 4 we see that P_k enhances from P_m almost parallally on both the scales. Finally, the deviations in observed galaxy power spectrum (P_g) are significantly larger on large scale compared to the small scale because of the extra GR corrections through $\mathcal{A}$ and the $\mathcal{B}$ terms in Eq. (5).

Conclusions

- Due to the general relativistic corrections (related to the peculiar velocity and Doppler effect) on and the extra effect from dark energy perturbation on large scale, the observed galaxy power spectrum enhances on larger scale compared to the small scale.
- The extra effect from the dark energy perturbation on large scale help us to distinguish different dark energy models more effectively on large scale compared to the small scale.
- The extra effect on large scale compared to the small scale decreases with increasing redshift because as redshift increases the effect of dark energy decreases.

Forthcoming Research

We aim to extend this study to massive gravity and generalized Proca theories for gravity.

References

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