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Effect of Dark Energy Perturbation On σ_8 Tension

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Abstract

The cosmological constant model (ΛCDM) not only suffers from many theoretical challenges, it also presents inconsistencies between some independent observations. There exists a tension of more than 3σ between the Planck CMB measurement and the redshift space distortion (RSD) measurements in the estimation of r.m.s matter power fluctuation in the $8h^{-1}$Mpc scale, σ_8. The scalar field dark energy models are potential alternate to the ΛCDM model, and resolve or at least alleviate the challenges and tension. The scalar field dark energy also cluster if the present value of the equation of state parameter deviate from -1. In this study we consider the tachyon scalar field dark energy and analyze the effect of perturbation on the σ_8 tension. We calculate the linear growth rate f for this model and compare it with ΛCDM model. We use values values of f σ_8 to compare the theoretical model with RSD data. Both the models are in good agreement with data. We present constraint on $\sigma_8 - \Omega_m$ plane and show that the tension is reduced below 2σ for the perturbed scalar field dark energy model.

Introduction

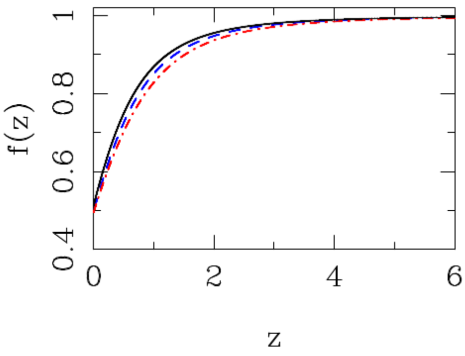
The present day acceleration of the Universe is discovered while explaining the observation of the Supernova Ia [1–4], and later conformed by other observations which includes observation of Baryon Acoustic Oscillations [5–8], Cosmic Microwave Background [9, 10] etc. The simplest and most popular model, which shows agreement with observational data, is cosmological constant model (ΛCDM model). This model fails on theoretical ground and suffers from cosmological constant problem, fine tuning problem and coincident problem [11–14]. On the other hand, there are some inconsistencies and tensions between independent observations in the estimations of cosmological parameters in the light of this model. Therefore, cosmologist search for alternative of this model assuming accelerated expansion is driven by a negative pressure medium called 'dark energy'. The most popular dark energy models are the barotropic fluid models, canonical and non-canonical scalar field models [15–22, 29]. These models too effectively explain the present day accelerated expansion and show good agreement with data. we need to break this degeneracy between models in order to find the true nature of the dark energy. Only background distance measurement can not break this degeneracy, we need to go to perturbation.

The cosmological tensions include the estimation of the Hubble constant H_0, the r.m.s. matter power fluctuation at $8h^{-1}$Mpc scale σ_8, S_8, the matter density parameter Ω_m, etc. The constraints on $\sigma_8 - \Omega_m$ plane is extracted from CMB data as well as from matter clustering data through redshift space distortion (RSD). It is found that there is a tension of more than 3σ between these two inde- pendent observations if we consider ΛCDM model [23, 26]. Many approaches have been made to generalize the ΛCDM model in order to resolve or alleviate this tension. We present an analysis of effect of perturbation in dark energy on this tension.

In the next section we introduce basic physical quantities to analyze clustering in the Universe. The RSD data used in this study are introduce in the section 3. We discus our result in the section 4. The summary and conclusions are presented in the section 5.

Clustering of Matter and Dark Energy

The scalar field dark energy models are potential alternate to the ΛCDM model. Here, we present analysis for a non-canonical scalar field model known as the tachyon model of dark energy. The background evolution of the Universe and constraints on the parameters are



studied in [29]. If the

Figure 1. *The evolution of the logarithmic growth rate with redshift at λ_p = 50 Mpc scale. The value of pa- rameter Ω_{m0} = 0.285. The solid black curve for ΛCDM model, whereas dashed blue and dashed-dot red curves are for perturbed tachyon model with exponential potential and with inverse square potential respectively.*

Present value of the equation of state parameter $w_{\varphi 0} \neq -1$, then the scalar field get perturbed and affects the growth of matter clustering [23]. The clustering of matter is quantify by the 'matter density contrast' given by

$$\delta(r, t) = \frac{\rho(r,t) - \bar{\rho}}{\bar{\rho}}, \qquad (2.1)$$

where $\bar{\rho}$ is the average matter density. The growth of the structures is quantify by the 'linear growth function' D^+_m, given by

$$D^+_m = \frac{\delta_m}{\delta_{m0}}, \qquad (2.2)$$

where δ_{m0} is the present value of matter density contrast. The growth rate of structures in the Universe is given by a logarithmic function called 'linear growth rate' (f) defined as

$$f = \frac{d\ln\delta}{d\ln a}. \qquad (2.3)$$

here, a is the scale factor of the expansion of the Universe. The clustering measurement provide the growth of structure in terms of $f\sigma_8$, where σ_8 is the r.m.s matter power fluctuation in the $8h^{-1}$Mpc scale. At a particular redshift z, this can be written as

$$\sigma_8(z) = \sigma_8(0)\frac{\delta_m(z)}{\delta_{m0}}. \quad (2.4)$$

In figure 1 we show the evolution of linear growth function f with redshift at scale λ_p = 50 Mpc. At sub-Hubble scale, the evolution of growth function D_m^+ is scale independent [23]. Therefore, the evolution of f shown in the figure 1 is applicable for all scales smaller than the Hubble scale. We see that the growth rate of structure is suppressed in the dark energy dominated era for all models. This suppression is large for dynamical dark energy with perturbed dark energy. For details of the effect of perturbed dark energy on matter clustering at the Sub-Hubble and super-Hubble scales refer to [23]. In the next section, we compare the models with the redshift space distortion data.

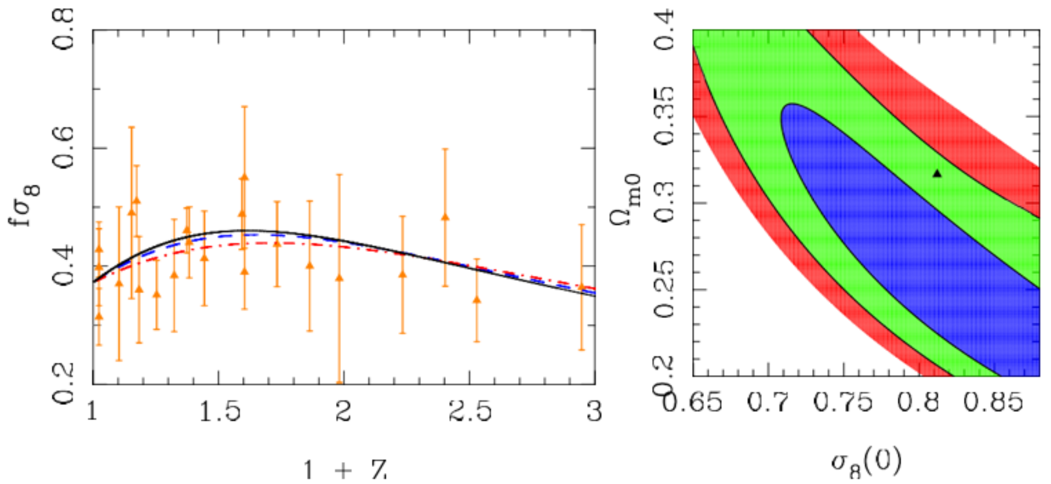


Figure 2. *On left panel, we show a comparison between dark energy models and RSD data with best fit values of parameters. On the right panel, we show marginalized constraints on $\Omega_{m0} - \sigma_8(0)$ plane for the tachyon scalar field dark energy model with inverse square potential. The black dot and triangle show the best fit values for Planck-2015 [24] and Planck-2018 [25] respectively.*

Redshift Space Distortion (RSD) Data

The values of f σ_8 is extracted from the redshift space distortion (RSD) measurements. We use 22 RSD data points from redshift 0.02 to 1.44 for this analysis. The 18 RSD data points are listed in table III of 'Gold-2017' compilation [26]. Other four data points at redshift 0.978, 1.23, 1.526 and 1.944 from [27]. All the RSD data points with the error in the measurement, and the fiducial cosmology are listed in [28].

We find the likelihood of the parameters by minimizing the χ^2 given by

$$\chi^2 = \sum_{i,j=1}^{22} [X_{th,i} - X_{obs,i}] C^{-1}_{i\,j} [X_{th,j} - X_{obs,j}], \quad (3.1)$$

where $C_{i,j}$ is the covariance matrix. The vectors X_{th} and X_{obs} contain the theoretical and observed values of f σ_8 respectively. We scale the theoretical value of f σ_8 by the ratio

$$r(z) = \frac{H(z)dA(z)}{H^{fid}(z)d^{fid}(z)}, \quad (3.2)$$

where $H(z)$ and $d_A(z)$ are the Hubble parameter and the angular diameter distance at redshift z respectively.

Constraints on σ8 −Ωm plane

In left panel of figure 2 we show the comparison between all three model with RSD data. We set the parameters Ω_{m0} and $\sigma_8(0)$ to their corresponding best fit values. The value of field $\varphi_{in}H_0 = 0.8$, and decreasing this value further means $w_{\varphi 0} \to -1$, then the difference between all three medels vanishes [23, 29]. Clearly, if $w_{\varphi 0} \neq -1$, then there is a significant difference between ΛCDM model and the perturbed dark energy model. This fact can be used to analyze the degeneracy between dark energy models.

On the right panel of the figure 2 we show the marginalized constraints on the $\Omega_{m0} - \sigma_8(0)$ plane for perturbed tachyon dark energy model. Here, blue, green and red regions show 68%, 95% and 99% confidence range, along with the best fit dot. We find that the constraints on Ω_{m0} and $\sigma_8(0)$ are $0.231_{-0.084}^{+0.126}$ and $0.853_{-0.144}^{+0.191}$ with 1σ confidence. The best fit values for Planck-2015 [24] and Planck-2018 [25] are shown by the black dot and triangle respectively. There is a tension of more then 3σ between Planck data and RSD data for ΛCDM model [23, 26]. The tension is less than 2σ for perturbed tachyon model. This alleviation is also true for other perturbed scalar field dark energy models.

Summary and Conclusions

In this study we show the effect of perturbation in the scalar field dark energy on the tension between the Planck CMB and redshift space distortion measurements (RSD) of the Ω_{m0}. We compare our result for perturbed tachyon scalar field dark energy model with smooth ΛCDM model. The ΛCDM model and the tachyon model, both, are in good agreement with the RSD data. There is significant difference between dark energy models if the equation of state $w_{\varphi 0}$ at present deviate from −1 (a cosmological constant like value). As the $w_{\varphi 0} \neq -1$, the background evolution for different models coincide, and only background distance measurements can not break the degeneracy between them.

We also show the constraints on $\Omega_{m0} - \sigma_8(0)$ plane. We find $\Omega_{m0} = 0.231_{-0.084}^{+0.126}$ and $\sigma_8(0) = 0.853_{-0.144}^{+0.191}$ at 1σ confidence. Our aim here is to show the alleviation of tension between observation on inclusion of perturbation in dark energy. The tension is more then 3σ for ΛCDM model. When we include perturbation in the dark energy this tension get alleviated and comes below 2σ.

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