Testing Modified gravity with CMB data and growth rate from Large Scale Structure Survey

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ABSTRACT
The abstract goes here. It describes the purpose of this paper.

Key words: gravitation; modified gravity; galaxies: statistics; cosmological parameters; large-scale structure of Universe

1 INTRODUCTION

The Genral Realtivity (GR) is by far most successful theory of gravity to describe the evolution of universe(Peebles 1980; Davis & Peebles 1983). The prediction of GR for the evolution of growth of structure is getting precise as we are improving on the precision of cosmological parameters with improved CMB measurement. The GR successfully explains almost all the observation except the physics of mysterious accelerated expansion of the universe and dark matter. The physical understanding of accelerated expansion of the universe is one of the most important challenge in front of modern physics (Riess et al. 1998; Perlmutter et al. 1999). The theoretical explanation of accelerated expansion in GR comes as cosmological constant Λ (Einstein 1915). The Λ is in good agreement with baryon acoustic oscilation (BAO) (Eisenstein et al. 2005; Cole et al. 2005; Hütsi 2006; Kazin et al. 2010; Percival et al. 2010; Reid et al. 2010; Aubourg et al. 2014; Anderson et al. 2014) , supernovae (Suzuki et al. 2012; Conley et al. 2011), and CMB (Planck Collaboration et al. 2014a; Bennett et al. 2013) observations. But, The vacuum energy density predicted by quantum field theory (Weinberg 1989) is many order of magnitude higher than observed Λ. Some alternative to Λ is proposed, which can be divided into two classes first modified gravity (Silvestri & Trodden 2009; Clifton et al. 2012) and second dynamical dark energy (Copeland et al. 2006).

A major challenge in front of modern cosmology is to do precision test of standard model of cosmology (ΛCDM-GR) and identify areas of tension. Any departure from standard ΛCDM is likely to be small and challenging to detect according to current Observations. In this 100th anniversary of General Theory of Relativity, we are in a unique position to test the theory to unprecedented precision with the modern observational probe. The deviation from ΛCDM-GR can be evaluated in mainly two different ways. One is by looking at extension of ΛCDM-GR by introducing additional parameters for dark energy equation of state and curvature of the universe. The other method is by replacing GR with modified gravity models. The three basic assumptions of ΛCDM-GR which are popularly tested are the curvature of the universe, nature of dark energy and law of gravitational interaction at large scale. The curvature of universe is measured by relaxing the assumption that spatial curvature is zero and allow Ω_K parameter to be free. The ΛCDM-GR assumes that dark energy equation of state is constant ($w = -1$). The popular approach to test the deviation of dark energy equation of state is by allowing w to be a free parameter. Another model to test the time-dependence of dark energy by parametrizing w in terms of w_0 and w_a using $w = w_0 + w_a \frac{z}{1+z}$. The nature of gravity in ΛCDM-GR is tested by replacing the GR with various modified gravity models. One of the important probe which gets affected by these modification is the growth rate. The modified gravity models generally predicts different growth rates, where as different dark energy model predict different evolution of growth rate with redshift.

The modern galaxy redshift survey have successfully measured the growth rate using Redshift Space Distortion (RSD). The distortion produced in the galaxy auto-correlation function due to the peculiar velocity component of the galaxy redshift is known as redshift space distortion. RSD on linear scales reflects the distribution of matter over-density and peculiar velocity of galaxies. Recent galaxy redshift surveys have provided the measurement of growth rate ($f\sigma_8(z)$) upto redshift of 0.8 , where f is logarithmic derivative of growth factor and σ_8 is the rms amplitude of matter fluctuation in a sphere of radius 8 h^{-1}Mpc. In this paper, we will test all the three assumptions of ΛCDM-GR listed above using the Planck CMB measurement (Planck Collaboration et al. 2014a) and latest RSD measurement from BOSS CMASS (Alam et al. 2015), SDSS LRG (Samushia et al. 2012), 6dFGRS(Beutler et al. 2012), 2dFGRS (Percival et al. 2004), WiggleZ (Blake et al. 2011a) and VIMOS Public Extragalactic Redshift Survey (VIPERS,de la Torre et al. (2013))

2 THEORY

We have studied three different parametrization of f(R) gravity in this paper. 1) f(R) gravity with one parameter B_o related to the compton scattering length. 2) sclar-tensot chameleon type theory 3) Linder's parametrization.

@Alessandra: could you please fill in detail about the above three models as we discussed.

3 OBSERVATIONS

We are using measurements of C_l from Planck 2013 (Planck Collaboration et al. 2014b)combined with the measurement of $f(z)\sigma_8(z)$ from various redshift surveys covering between $z = 0.06$ to $z = 0.8$ listed in Table 1 as our main data points. We briefly describe each of the survey and $f\sigma_8$ measurement.

correlation between different data point. Does it makes sense to say that fraction of overlapping volume gives the correlation between the measurement in the table. The measurement used has negligible overlapping volume!!

3.1 6dFGRS

The 6dFGRS (6 degree field galaxy redshift survey have observed 125000 galaxy in near infrared band across 4/5th of southern sky Jones et al. (2009). The survey covers redshift range $0 < z < 0.18$, and has efective volume equivalent to 2dFGRS (Percival et al. 2004) galaxy survey. The redshift space distortion(RSD) measurement was obtained using a subsample of the survey consisting of 81971 galaxies (Beutler et al. 2012). The measurement of $f\sigma_8$ was obtained by fitting 2D correlation function using streaming model and fitting range 16-30 Mpc/h. The Alcock-Paczynski effect has been taken into account and it has a negligible effect. The final measurement uses WMAP7 (Bennett et al. 2013) likelihood in the analysis. To be able to use this data point we need to account for the transformation to the planck best fit cosmology.

3.2 2dFGRS

The 2dFGRS (2 degree field galaxy redshift survey) obtained spectra for 221414 galaxies in visible band on the southern sky (Colless et al. 2003). The survey covers redshift range $0 < z < 0.25$ and has effective area of 1500 square degree. The redshift space distortion measurement was obtained by linearly modeling the observed distortion after splitting the over-density into radial and angular components (Percival et al. 2004). The parameters were fixed at different values $n_s = 1.0$,$H_0 = 72$. The results were marginalized over power spectrum amplitude and $b\sigma_8$. We are not using this measurement in out analysis for two reasons. First the survey has huge overlap with 6dFGRS which will lead to strong correlation between the two measurement and second the cosmology assumed is quite far from WMAP7 and Planck where our linear theory approximation to shift the cosmology might fail.

Table 1. Measurement of $f(z)\sigma_8(z)$ from various galaxy redshift survey covering redshift between 0.06 to 0.8.

z	$f\sigma_8(z)$	1/k[h /Mpc]	Survey
0.067	0.42 ± 0.05	16.0 –30	6dFGRS(2012)
0.17	0.51 ± 0.06	6.7 – 50	2dFGRS(2004)
0.22	0.42 ± 0.07	3.3 – 50	WiggleZ(2011)
0.25	0.35 ± 0.06	30 – 200	SDSS LRG (2011)
0.37	0.46 ± 0.04	30 – 200	SDSS LRG(2011)
0.41	0.45 ± 0.04	3.3 – 50	WiggleZ(2011)
0.57	0.462 ± 0.041	25 –130	BOSS CMASS
0.6	0.43 ± 0.04	3.3 – 50	WiggleZ(2011)
0.78	0.38 ± 0.04	3.3 – 50	WiggleZ(2011)
0.8	0.47 ± 0.08	6.0 – 35	Vipers(2013)

3.3 WiggleZ

The WiggleZ Dark Energy Survey is a large scale galaxy redshift survey of bright emission line galaxies. It has obtained spectra for around 200,000 galaxies. The survey covers redshift range $0.2 < z < 1.0$ and covering effective area of 800 square degree of equatorial sky (Blake et al. 2011b). The redshift space distortion(RSD) measurement was obtained using a sub-sample of the survey consisting of 152,117 galaxies. The final result was obtained by fitting the power spectrum using Jennings et al. (2011) model in four non-overlapping slices of redshift. The measured growth rate is $f\sigma_8(z) = (0.42 \pm 0.07, 0.45 \pm 0.04, 0.43 \pm 0.04, 0.38 \pm 0.04)$ at effective redshift $z = (0.22, 0.41, 0.6, 0.78)$ with non-overlaping redshift slices of $z_{slice} = ([0.1, 0.3], [0.3, 0.5], [0.5, 0.7], [0.7, 0.9])$ respectively. We can assume the covariance between the different measurement to be zero because they have zero overlapping volume.

3.4 SDSS-LRG

The Sloan Digital Sky Survey (SDSS) data release 7 (DR7) is a large-scale galaxy redshift survey of Luminous Red Galaxies (LRG) (Eisenstein et al. 2011). The DR7 has obtained spectra of 106,341 LRGs covering 10,000 square degree in redshift range $0.16 < z < 0.44$.The RSD measurement was obtained by modeling monopole and quadruple moment of galaxy auto-correlation function using linear theory. The data was divided in two redshift bins $0.16 < z < 0.32$ and $0.32 < z < 0.44$. The measurement of growth rate are $f\sigma_8(z) = (0.3512 \pm 0.0583, 0.4602 \pm 0.0378)$ at effective redshift of 0.25 and 0.37 respectively (Samushia et al. 2012). These measurements are independent because there is no overlapping volume between the two redshift slice.

3.5 BOSS CMASS

Sloan Digital Sky Survey (SDSS) Baryon Oscillation Spectroscopic Survey (BOSS; Dawson et al. (2013)) targets high redshift ($0.4 < z < 0.7$) galaxies using a set of color-magnitude cuts. The growth rate measurement uses the CMASS sample of galaxies (Bolton et al. 2012) from data release 11 (Alam et al. 2015). The CMASS sample has 690,826 Luminous Red Galaxies (LRGs) covering 8498 square degrees in the redshift range $0.43 < z < 0.70$, which correspond to an effective volume of 6 Gpc^3. The $f\sigma_8$ is measured by modeling the monopole and quadruple moment of galaxy auto-correlation using Convolution Lagrangian Perturbation Theory (CLPT; Carlson et al. (2013)) in combination with Gaussian Streaming model (Wang et al. 2014). The reported measurement of growth rate is $f\sigma_8 = 0.462 \pm 0.041$ at effective redshift of 0.57 (Alam et al. 2015).

3.6 VIPERS

VIMOS Public Extragalactic Redshift Survey (VIPERS,de la Torre et al. (2013)) is a high redshift small area galaxy redshift survey. It has obtained spectra for 55,358 galaxies covering 24 square degree in the sky from redshift range $0.4 < z < 1.2$. The measurement of growth factor uses 45,871 galaxies covering the redshift range $0.7 < z, 1.2$. The $f\sigma_8$ measurement is obtained by modeling the monopole and quadruple moments of galaxy auto-correlation function between the scale 6 h^{-1}Mpc and 35 h^{-1}Mpc. They have reported $f\sigma_8 = 0.47 \pm 0.08$ at effective redshift of 0.8.

3.7 Planck CMB

Planck is a space mission dedicated to measurement of CMB anisotropies. It is the third-generation of CMB experiment following COBE and WMAP. The primary aim of the mission is to measure the temperature and polarization anisotropies over the entire sky. The Planck mission provide a high resolution map of CMB anisotropy which is used to measure angular power spectrum C_ℓ at the last scattering surface. The Planck measurement helps us constrain the background cosmology to unprecedented precision. We are using the CMB measurement from planck satellite in order to constrain cosmology. We have assumed that the Planck measurement is independent of the measurement of growth rate from various galaxy redshift survey.

4 POTENTIAL SYSTEMATICS

The modified gravity theories considered in this paper have additional free parameter which provide extra degree of freedom while predicting evolution of growth factor compared to General Relativity. The $f\sigma_8$ measurement we are using in this analysis have been measured over last decade using completely different data and analysis pipeline as part of various different survey. It is important to account for some crucial differences in order to use these measurements in our analysis. We have looked at following different aspect of measurement and theoretical prediction before using them in our analysis.

4.1 Fiducial Cosmology of the growth rate ($f\sigma_8$)

The measurements of $f\sigma_8$ is done over the time when we had transition from WMAP best fit cosmology to the Planck best fit cosmology. Since we are using Planck likelihood in our analysis, We have decided to convert all the measurement to planck cosmology. The 3 dimensional correlation function can be transformed from WMAP to the planck cosmology by using Alcock-Paczynski effect (Alcock & Paczynski (1979)).

$$\xi_{planck}(r_\parallel, r_\perp, \phi) = \xi_{WMAP}(\alpha_\parallel r_\parallel, \alpha_\perp r_\perp, \phi) \tag{1}$$

Where $\alpha_\parallel$ is the ratio of hubble parameter ($\alpha_\parallel = H_{WMAP}/H_{planck}$) and $\alpha_\perp$ is the ratio of angular diameter distance ($\alpha_\perp = D_A^{planck}/D_A^{WMAP}$). The $r_\parallel$, $r_\perp$ are pair separation along line of sight and perpendicular to the line of sight and ϕ is the angular position of pair separation vector in the plane perpendicular to the line of sight from a reference direction. In practice the correlation function is isotropic along ϕ. We can calculate the corresponding power spectrum by applying Fourier transform to correlation function.

$$P_{planck}(k_\parallel, k_\perp, k_\phi) = \int dr_\parallel dr_\perp r_\perp d\phi \xi_{planck}(r_\parallel, r_\perp, \phi) e^{-i\vec{k}.\vec{r}} \tag{2}$$

$$= \int dr'_\parallel dr'_\perp \frac{r'_\perp}{\alpha_\parallel \alpha_\perp^2} \xi_{WMAP}(r'_\parallel, r'_\perp, \phi) e^{-i\vec{k'}.\vec{r'}} \tag{3}$$

$$= \frac{P_{WMAP}(k_\parallel/\alpha_\parallel, k_\perp/\alpha_\perp, k_\phi)}{\alpha_\parallel \alpha_\perp^2} \tag{4}$$

The kaiser formula for RSD gives the redshift space correlation function as $P_g^s(k,\mu) = b^2 P_m(k)(1+\beta\mu^2)^2$ **?**. Using the linear theory kaiser prediction and above approximation between WMAP and planck power spectrum We can get a relation to transform the growth function from WMAP to planck cosmology.

$$\frac{1+\beta_{planck}\mu'^2}{1+\beta_{WMAP}\mu^2} = C\sqrt{\frac{P_{planck}(k',\mu')}{P_{WMAP}(k,\mu)}} \tag{5}$$

$$= C\sqrt{\frac{1}{\alpha_\parallel \alpha_\perp^2}} \tag{6}$$

Where C is the ratio of isotropic matter power spectrum with WMAP and planck cosmology integrated over scale used in β measurement.

$$C = \int_{k_1}^{k_2} dk \sqrt{\frac{P^m_{WMAP}(k)}{P^m_{planck}(k')}} \tag{7}$$

When right hand side of equaion(6) is close to 1 then we can approximate the above equation as follow.

$$\beta_{planck} = \beta_{WMAP} C \frac{\mu^2}{\mu'^2}\sqrt{\frac{1}{\alpha_\parallel \alpha_\perp^2}} \tag{8}$$

The ratio $\frac{\mu^2}{\mu'^2}$ can be obtained using simple trigonometry which gives following equation, where the last equation is aprroximation for $\alpha_\parallel^2 \approx \alpha_\perp^2$.

$$\frac{\mu^2}{\mu'^2} = \alpha_\perp^2 + (\alpha_\parallel^2 - \alpha_\perp^2)\mu^2 \approx \alpha_\perp^2 \tag{9}$$

we can substitute equation(9) in equation(8) in order to get the required scaling for f(growth factor) assuming that bias measured is proportional to the σ_8 of the cosmology used.

$$\beta_{planck} = \beta_{WMAP} C\sqrt{\frac{\alpha_\perp^2}{\alpha_\parallel}} \tag{10}$$

$$f\sigma_{8planck} = f\sigma_{8WMAP} C\sqrt{\frac{\alpha_\perp^2}{\alpha_\parallel}} \left(\frac{\sigma_8^{planck}}{\sigma_8^{WMAP}}\right)^2 \tag{11}$$

We have tested prediction of equation (11) against the measurement of $f\sigma_8$ reported in Table 2 of Alam et al. (2015) at redshift 0.57 using both Planck and WMAP cosmology.

4.2 Scale dependence

The General Relativity predicts scale independent evolution of matter density field by predicting scale independent growth factor. One of the important feature of the modified gravity theories we are considering is that they predict a scale dependent growth factor which has a transition from high to low growth at certain scale which depends on the redshift z and the model parameters. The mesurement we have from all the survey assumes a scale-independent $f\sigma_8$ and use characterisitic length scale while analysing data. In order to account for all this effect we have done our analysis in two different ways. In the first method, we assume that the measurement correspond to an effective k and in the second method, we treat the average theoretical prediction over range of k used in $f\sigma_8$ analysis.

4.3 Assumption of GR in the survey analysis

Generally all these measurement are independent of model of gravityand should be good to test alternate gravity model explain how?

Anything else!! worry about systematic effects

5 ANALYSIS

We have measurement of $f\sigma_8$ from various survey covering redshift range 0.06-0.8 (see Table: 1). We first correct these measurement for the shift from WMAP cosmology to planck cosmology as described in section(4.1). The next step is to evaluate prediction from different modified gravity theory by evolving full set of linear perturbation equation. The theoretical predictions for $f\sigma_8$ is generally scale and redshift dependent. Therefore, We consider two case for theoretical prediction which is to evaluate $f\sigma_8$ at 1) effective k and 2) average over k. We also predict C_l^{TT} for different modified gravity theory and finally define our likelihood, which consist of two parts one by matching planck temperature fluctuation C_l^{TT} and other by matching growth factor from Table 1. Therefore we define the likelihood as follow:

$$\mathcal{L} = \mathcal{L}_{planck}\mathcal{L}_{f\sigma_8} \tag{12}$$

$$\mathcal{L}_{f\sigma_8} = e^{-\chi^2_{f\sigma_8}/2} \tag{13}$$

$$\chi^2_{f\sigma_8} = \Delta f\sigma_8 C^{-1} \Delta f\sigma_8^T \tag{14}$$

The $\Delta f\sigma_8$ is the deviation of theoretical prediction from the mesurement and C^{-1} is the covariance which has diagonal error for different survey and correlation between measurement as described in section[**??**]. This Likelihood is sampled using modified version of COSMOMC (Lewis & Bridle 2002; Hojjati et al. 2011). We are sampling over 6 cosmology parameter $\{\Omega_b h^2, \Omega_c h^2, 100\Theta_{MC}, \tau, n_s, log(10^{10}A_s)\}$ and all the 18 planck nuisance parameter as described in Planck Collaboration et al. (2014a) with the respective extension parameters or modified gravity parameters. We have used prior on all of the parameter same as the priors given in Planck Collaboration et al. (2014a) and the prior on parameters of modified gravity model is given in Table :[**??**].

6 RESULTS

We have combine CMB data set and measurement of growth from various redshift survey in order to constrain the parameters of standard cosmology (ΛCDM), extended cosmology models and modified gravity. For all the models considered in this paper our analysis gives consistent constraint for the standard ΛCDM parameters ($\{\Omega_b h^2, \Omega_c h^2, 100\Theta_{MC}, \tau, n_s, log(10^{10}A_s)\}$). The Figure 2 shows the constraint on Ω_m- σ_8 plane for ΛCDM, wCDM, kCDM, $f(R)$,Chameleon gravity and Linder γ parametrization. All the model gives similar precision for this parameter space except the kCDM model. The possibility of having non-zero spatial curvature expand the feasible region in Ω_m-σ_8.

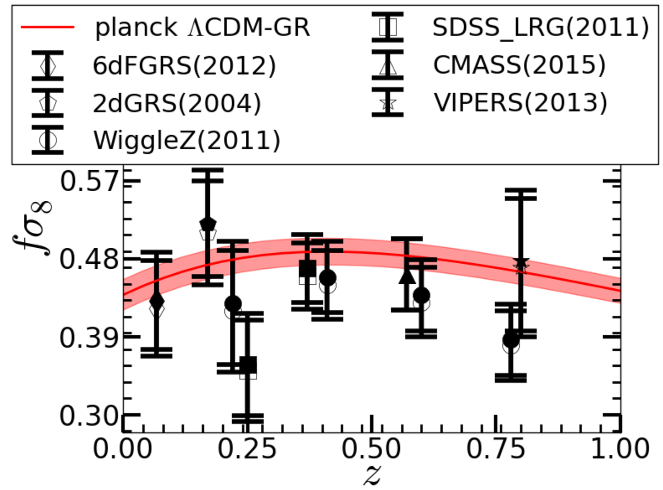

Figure 1. The measured $f\sigma_8$ from different survey covering redshift range $0.06 < z < 0.8$. The empty markers represents the reported measurement of $f\sigma_8$ and the filled marker are for the corrected values for Planck Comsology. The red band shows the Planck 1σ prediction.

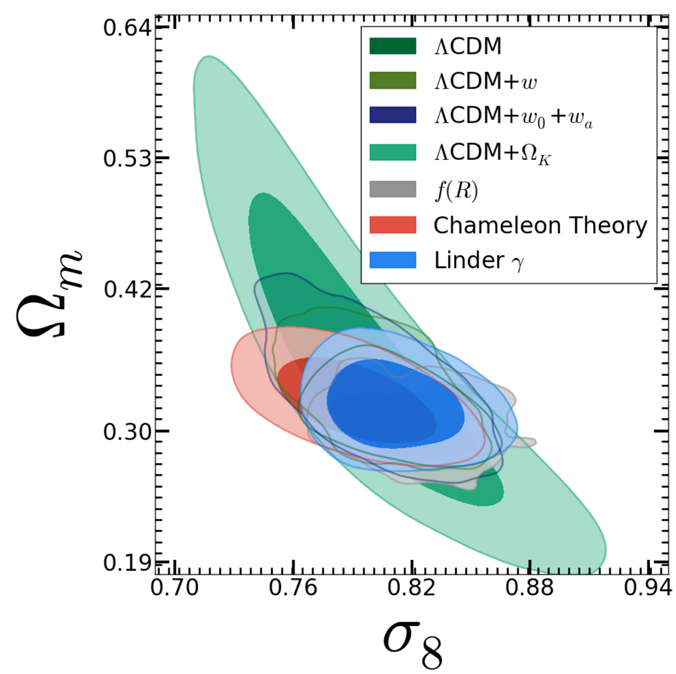

Figure 2. The figure shows the 1σ and 2σ region for each of the model consider in this paper in Ω_m-σ_8 plane. It shows that the posterior likelihood is consistent for each of the model in this parameter space. All the model have similar constraint in this space except kCDM.

6.1 ΛCDM-GR

The Figure 3 shows the one dimensional marginalized likelihood for standard ΛCDM-GR cosmology. Our parameter contraints are

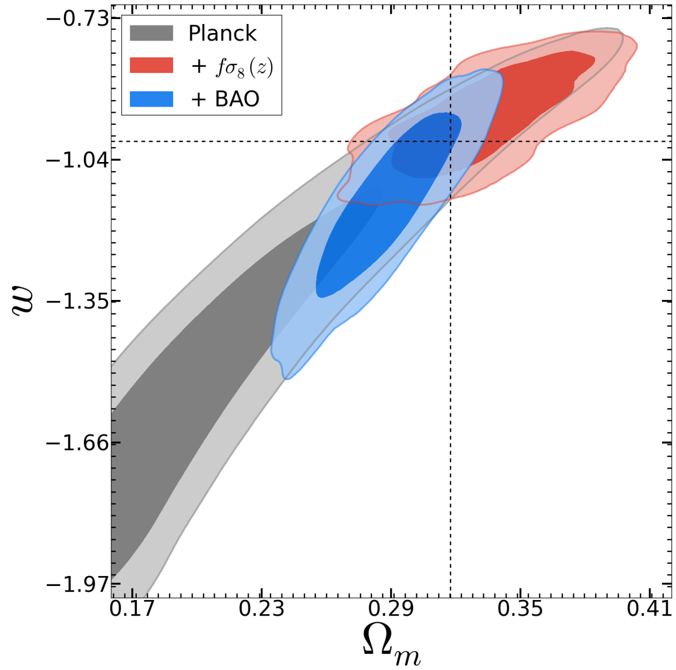

Figure 4. The two dimensional posterior likelihood w and Ω_m for wCDM. The grey contour is for Planck, blue contour is combined constraint from Planck and BAO. The red contour represents our results while combining Planck with $f\sigma_8$.

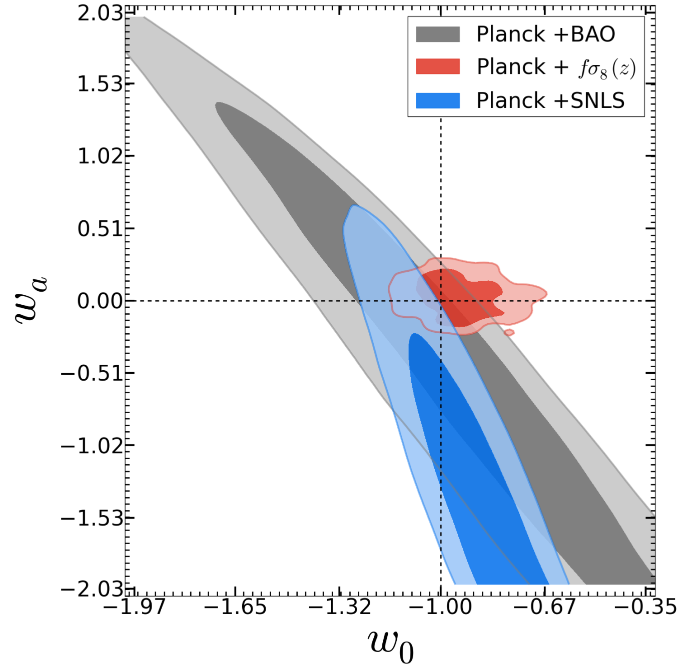

Figure 5. The two dimensional posterior likelihood of w_0 and w_a for time-dependent extension. The grey contour is for Planck, blue contour is combined constraint from Planck and BAO. The red contour represents our results while combining Planck with $f\sigma_8$.

completely consistent with the planck 2013 results. Adding measurement of growth rate with planck contraint doesn't improve the precision of cosmology because the precision of planck prediction (pink band in Figure 1) is much smaller than the precision of the measurement of growth factor (black points in Figure 1).

6.2 Dark Energy Equation of state (wCDM)

We have looked at the wCDM (one parameter extension of ΛCDM) , where w is the dark energy equation of state. The Figure 4 shows the two dimensional likelihood of of w and Ω_m. The grey contour are planck only contraint, blue contour shows planck combined with the BAO (Baryon Acoustic Oscillation cite paper) measurement and red contours are our result planck combined with growth factor ($f\sigma_8$) measurement. We obtain $w = x \pm y$ (z% measurement) which is consistent fiducial value of $w = -1$ for ΛCDM. The constraint we obtained is similar in precision as compared to BAO but has different degeneracy. Therefore combining planck with BAO and RSD together might give a much stronger constraint on dark energy equation of state w. But, That will require taking care of covariances between the BAO and RSD and they come from exactly same galaxy sample.

6.3 Time-dependent Dark Energy ($w_0 w_a$CDM)

The wCDM model which propose a constant dark energy is limited in its physical characteristic. Many model propose time-dependent which is popularly tested using linear relation $w(z) = w_0 + w_a \frac{z}{1+z}$ with w_0 and w_a as free parameter. This captures the slowly rolling minimally-coupled scalar field, low-redshift behavior of light. The dynamical evolution of $w(z)$ can change the growth factor significantly and leave a imprint on the CMB. The combination of CMB and collection of growth factor at different redshift is a unique way to test the time-dependent dark energy model.

Figure 5 shows the 1σ and 2σ region for (w_0, w_a). The grey contour is from the combination of Planck and BAO. The blue contours is from Planck and SNLS. The red contour is our measurement by combining the growth rate measurements with Planck. The ΛCDM-GR prediction $(w_0, w_a) = (-1, 0)$ is completely consistent with our posterior. We have obtained constraint on $w_0 = x \pm y$ (z% measurement) and $w_a = x \pm y$ (z% measurement) which is much stronger constraint than the existing measurements.

6.4 Spatial Curvature (kCDM)

We consider a model with spatial curvature parametrized with Ω_K as free parameter called kCDM along with ΛCDM parameters. The Figure 6 shows the posterior for the Ω_K and Ω_m plane. We measure $\Omega_K = x \pm y$ (z % measurement) shown by red shaded region by combining planck and $f\sigma_8(z)$ measurement.The grey region is using planck only measurement which gives $\Omega_K = x \pm y$ (z % measurement). The blue shaded region represents the constraint from planck and BAO combined. The BAO is much superior probe to constrain the spatial curvature of the universe compared to RSD. It will be interesting to see if RSD and BAO combined will give any different result.

6.5 Chameleon Gravity

The three parameters of Chameleon gravity (β_1, B_0, s) is constrained with the standard ΛCDM parameters using planck and $f\sigma_8(z)$ measurement. The Chameleon theory predicts a scale dependent growth rate ($f\sigma_8(k, z)$) where as the measurement are at some effective k. We have used two different approach to incorporate the k-dependence in our analysis. The Figure 7 shows the two

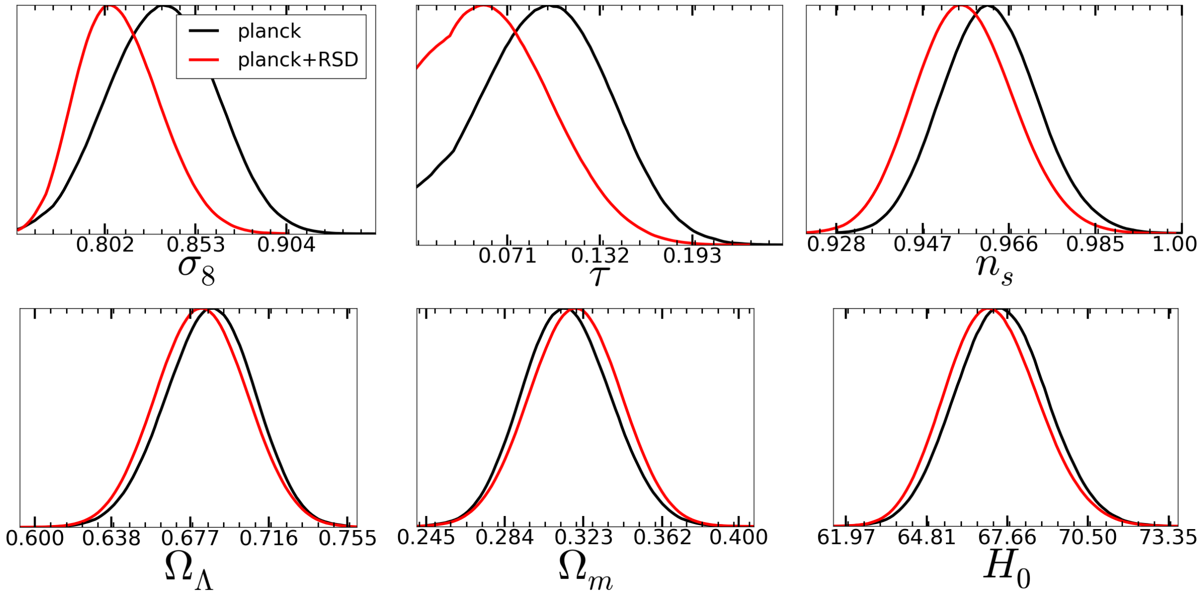

Figure 3. ΛCDM-GR: We use GR as the model for gravity to determine the growth factor and fit for $f\sigma_8$ measurement with planck likelihood. The two most prominent effect are in optical depth τ and scalar amplitude of primordial power spectrum A_s. Which is also reflected in the derived parameter σ_8 and mid redshift of re-ionization z_{re}.

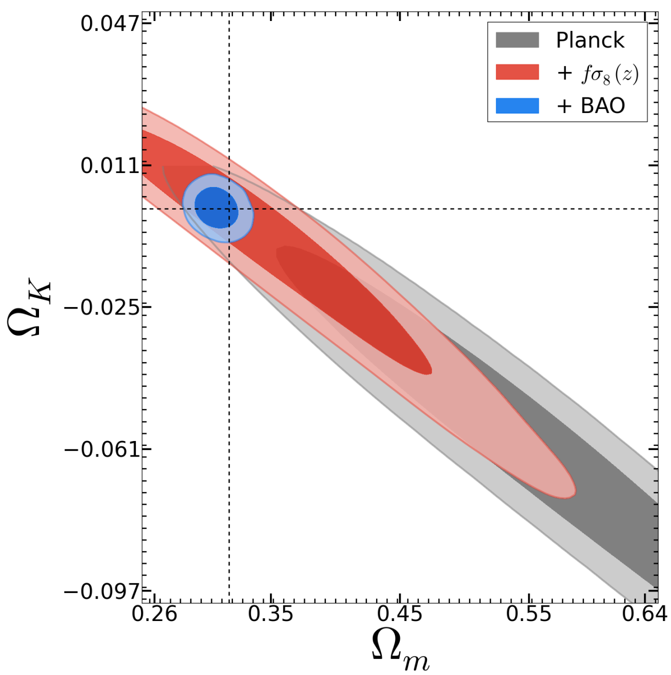

Figure 6. The two dimensional posterior likelihood of Ω_k and Ω_m for kCDM. The grey contour is for Planck, blue contour is combined constraint from Planck and BAO. The red contour represents our results while combining Planck with $f\sigma_8$

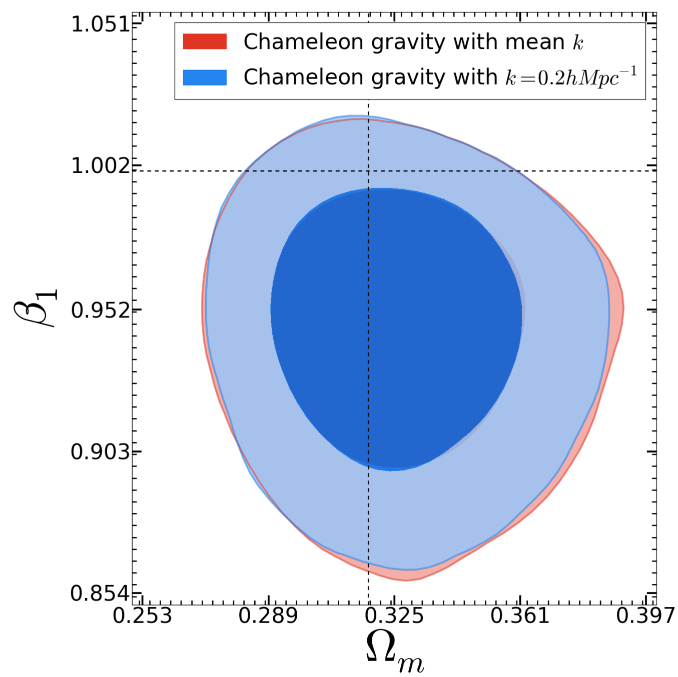

Figure 7. Chameleon

dimensional posterior in β_1 and Ω_m plane. The blue contours are likelihood while evaluating the growth rate at an effective k where red contour is for the case when we use effective growth rate which is averaged over scales used in the actual $f\sigma_8$ measurement. We obtained $\beta_1 = x \pm y$ (z % measurement), which is an improvement by a factor of X on the previous constraint $\beta_1 = x \pm y$ (z % measurement) using power spectrum (cite the Alireza paper).

The growth rate constrain the other two parameter B_0 and s of the model very weakly. You can see some of the contours in Appendix (add an appendix for this part).

6.6 Linder's γ_L parametrization

The general theory of relativity predicts the precise value of growth factor in the linear regime to be $f = \Omega_m^{0.545}$. In order to test the deviations from GR we have parameterized the growth factor using

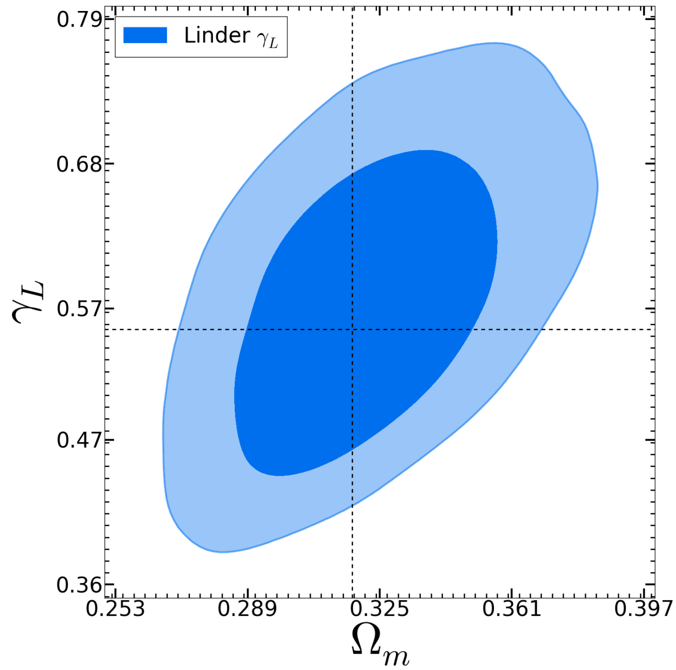

Figure 8. Linder

Linder γ_L (cite Linder & Cahn 2008) as $f = \Omega_m^{\gamma_L}$. The marginalized two dimensional likelihood for Ω_m and γ_L is shown in Figure 8. We have obtained $\gamma_L = x \pm y$ (z% measurement) completely consistent with the general relativity prediction.

6.7 $f(R)$ theory

We consider one parameter (B_0) model of $f(R)$ gravity. The parameter B_0 parameterize the deviation from ΛCDM-GR. The model approaches GR when B_0 is zeros. We find that the B_0 parameter is constrained to be $B_0 < 1.5 \times 10^{-5}$ (1σ C.L.). Compare the result with literature.

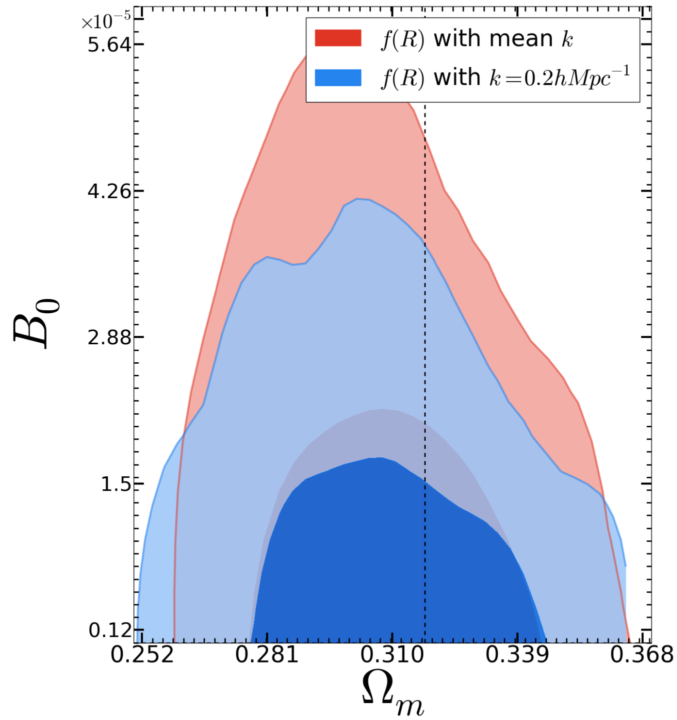

Figure 9. fR

7 DISCUSSION

Discuss the resuts!!

S .A . would like to thank ... S. H. would like to thank ... A.S would like to thank ... S. A . and S.H are supported by NASA for this work. This work made extensive use of the NASA Astrophysics Data System and of the `astro-ph` preprint archive at `arXiv.org`.

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