Constraints on the quintessence model with Yukawa interaction from Planck 2015 and weak lensing data

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We consider a quintessence model with Yukawa interaction between dark energy and dark matter and constrain this model by employing the most recent cosmological data including the latest cosmic microwave background measurements from Planck 2015 and the weak gravitational lensing measurements from Kilo Degree Survey (KiDS). We find that the interaction in the dark sectors is compatible with the observations. The updated Planck data can significantly improve the constraints compared with the previous results from Planck 2013, while the KiDS data has less constraining power than Planck. The Yukawa interaction model is found to be able to moderately alleviate the discordance between KiDS and Planck as previously inferred from the standard Lambda cold dark matter model.

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I. INTRODUCTION

Planck Collaboration has recently released their latest results on the cosmic microwave background (CMB) anisotropies [1], which provide the utmost observations on temperature and polarization of the photons from the last scattering surface. The updated data have made significant improvements compared with the previous data in 2013. This allows the derivation of more reliable scientific results and tighter constraints on the cosmological models.

The standard Lambda cold dark matter (ΛCDM) model is the most accepted model to explain the cosmic acceleration of our Universe at present. In this model the driving force of the Universe acceleration is assumed due to the cosmological constant Λ.

Although ΛCDM model is proved to be consistent with a lot of observations, it still faces some challenges. Recently, the ΛCDM model was examined by employing weak lensing data taken from a 450-deg2 observing field of the Kilo Degree Survey (KiDS) [2], where the cosmic shear is measured from distorted images of distant galaxies which can effectively map a three-dimensional dark matter structure in the late universe. It was disclosed that there exists a “substantial discordance” inferred from the ΛCDM model between the KiDS data [2–5] and the Planck 2015 CMB data [6, 7] and the tension is at the level of 2.3σ.

Besides the discordance between weak lensing measurements and the CMB measurements, the standard ΛCDM model is also challenged by other observations. For example, the value of the Hubble constant which is directly measured by Hubble Space Telescope (HST) presents about 3σ tension in comparison with the value inferred from CMB measurements if the ΛCDM model is considered [8, 9]. Meanwhile, another evidence against the standard ΛCDM model has been presented by the Baryon Oscillation Spectroscopic Survey (BOSS) experiment of the Sloan Digital Sky Survey (SDSS)[10], which is based on the measurements of the baryon acoustic oscillations (BAO) flux correlation functions of the Lyman-α forest from 158,401 quasars at high redshifts (2.1 ≤ z ≤ 3.5). Their results indicate a 2.5σ deviation from the ΛCDM model in the measurements of the Hubble constant and angular distance at an average redshift z = 2.34. Recently, the Experiment to Detect the Global Epoch of Reionization Signature (EDGES) reported the detection of an absorption profile in the sky-averaged radio spectrum centered at 78 MHz [11]. Their observation indicates a 21 centimeter signal with an amplitude of 0.5 kelvin, which is more than a factor of two greater than the theoretical prediction of the standard cosmological paradigm [12].

Theoretically, ΛCDM model suffers more fierce challenges, such as the cosmological constant problem [13], i.e., the observed value is many orders of magnitude smaller than the prediction of quantum field theory, and the coincidence problem [14], i.e., the cosmological constant of the ΛCDM model is difficult to explain why the dark energy dominates evolution in the late universe and why the Universe is accelerating just now but neither earlier nor later.

Due to these observational and theoretical problems in the standard ΛCDM model, there are a lot of attempts to find a more preferable model which can solve or alleviate these problems and explain the late time accelerated expansion of our Universe. Considering that dark energy and dark matter are two major components in the uni-
verse, it is natural, in the framework of field theory, to consider whether these two dark sectors have some inevitable interactions rather than evolve individually. It was argued that an appropriate interaction can provide a mechanism to alleviate the coincidence problem [15–22]. And it can accommodate an effective dark energy equation of state in the phantom region at the present time [23]. Since the lack of information on the nature and dynamics of dark energy and dark matter, it is difficult to drive the precise form of the interactions. Many alternative models have been proposed in the literature from phenomenology or field theory [15, 16, 18, 20, 21, 24–27].

For a review on the interaction between dark matter and dark energy, please refer to [28]. In this work we will concentrate on the scenario in which dark matter takes the form of a spin $\frac{1}{2}$ fermionic field and dark energy is described by an evolving and fluctuating scalar field, the quintessence. An interaction between these two components will affect the expansion history of the Universe and the evolution of the density perturbation, changing the growth history of cosmological structure. Consequently, the interaction could be constrained with observations of the background evolution and the emergence of large scale structure. Following [29], we will consider a Yukawa coupling of the dark energy field to the dark matter, which is renormalizable and has been well studied in the cosmology [30, 31].

The main motivation of this paper is to confront the Yukawa interaction model to the latest cosmological data, including the updated CMB data from Planck 2015 and the recent weak gravitational lensing data from KiDS. We are going to compare the constraints with the previous results from Planck 2013 [29] and to see whether the updated precise data can help to improve the limits on the cosmological parameters. Moreover, we will investigate the discordance problem between Planck and KiDS with the Yukawa interaction model and check whether an appropriate interaction can help to alleviate the tension between these two datasets.

The paper is organized as follows. In Section II we describe the Yukawa interaction model with background dynamics equations and linear perturbations. In Section III we introduce the observational datasets we are going to use. In Section IV we compare Planck 2015 constraint results with the previous results from Planck 2013, and investigate whether the Yukawa interaction model can help to alleviate the $\Lambda$CDM discordance problem between KiDS and Planck datasets. Finally, we present our conclusions in Section V.

## II. THE YUKAWA INTERACTION MODEL

We consider a quintessence model with an interaction between two dark sectors, where dark matter is described by a spin $\frac{1}{2}$ fermionic field and dark energy is described by a canonical scalar field. The action for this model is given by

$$S = \int d^4x\sqrt{-g}\left\{\frac{1}{2\kappa}R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - m(\phi)\bar{\psi}\psi + \mathcal{L}_K[\psi]\right\},$$

(1)

where $g$ is the determinant of the metric, $R$ is the Ricci scalar and $\kappa = 8\pi G$ where $G$ represents the gravitational constant. $\phi$ is the scalar field and its potential function $V(\phi)$ can be chosen freely. To be specific, in this paper we will study the exponential form $V(\phi) = A e^{-\lambda \phi/M_{pl}}$, where $A$ is a normalization constant, $\lambda$ is a dimensionless parameter and $M_{pl} = \sqrt{8\pi G}$ is the reduced Planck mass. $\psi$ is the fermionic field and $\mathcal{L}_K[\psi]$ is the kinetic part of the fermionic Lagrangian. $m(\phi)$ is the effective fermionic mass and the choice of it represents the coupling to $\psi$. In our model the function $m(\phi)$ is given by $m(\phi) = M - \beta \phi$, where $M$ is the fermionic mass and $\beta$ is the Yukawa coupling constant. This coupling can be treated as an external source in the conservation equations for the dark sectors of the Universe

$$\nabla_\mu T_{(c)\mu} = -Q_\mu,$$

(2)

$$\nabla_\mu T_{(d)\mu} = Q_\mu,$$

(3)

where $\nabla_\mu$ represents a covariant derivative, $T_{(c)\mu}$ is the stress energy tensor of the ‘c’ component in the Universe, the subscripts ‘c’ denotes dark matter and ‘d’ denotes dark energy. The source term $Q_\mu$ implies that these two components are not conserved, while for the whole system the energy momentum conservation still holds.

We assume that our Universe is described by a flat Friedmann-Lemaître-Robertson-Walker (FLRW) metric, in which the line element can be written as

$$ds^2 = -a^2(\eta)d\eta^2 + a^2(\eta)d^3x^i,$$

(4)

where $\eta$ is the conformal time and $a(\eta)$ is the scalar factor of the universe. For the rest of the paper, dot will denote the derivative with respect to conformal time. The zero-component of equations (2) and (3) provide the conservation equations for the energy densities of the dark sectors

$$\dot{\rho}_c = -3H\rho_c - Q_0,$$

(5)

$$\dot{\rho}_d = -3H\rho_d(1 + \omega) + Q_0,$$

(6)

where $H = \frac{\dot{a}}{a}$ is the Hubble function and $\omega \equiv P_d/\rho_d$ is the dark energy equation of state. Here we treat each component of the dark sectors as a fluid with the general stress-energy tensor $T_{\mu\nu} = (\rho_c + P_c)u_\mu u_\nu + P_c g_{\mu\nu}$, where $u_\mu = (-a,0,0,0)$ is the fluid 4-velocity. Dark energy is described by a scalar field $\phi$ rolling down a self-interaction potential $V(\phi)$, such that its energy density and pressure can be expressed as

$$\rho_d = \frac{\dot{\phi}^2}{2a^2} + V(\phi), \quad P_d = \frac{\dot{\phi}^2}{2a^2} - V(\phi).$$

(7)
The external source term $Q_{\mu}$ is related to the effective fermionic mass $m(\phi)$ via the expression

$$Q_{\mu} = -\frac{\partial \ln m(\phi)}{\partial \phi} \rho c \nabla_{\mu} \phi,$$

which gives the coupling term

$$Q_{\phi} = \frac{\beta}{M - \beta \phi} \rho c \frac{d}{d\phi} \phi,$$

where $r \equiv \frac{\beta}{M}$. We can rewrite the conservation equations (5) and (6) as

$$\dot{\rho}_c + 3H\rho_c = -\frac{r}{1 - r\phi} \rho c \dot{\phi},$$

$$\dot{\rho}_d + 3H\rho_d(1 + \omega) = \frac{r}{1 - r\phi} \rho c \dot{\phi}.$$  

To avoid the diverging point at $r\phi = 1$ we will stay in the region $r\phi < 1$. The signs of $r$ and $\dot{\phi}$ determine the direction of the energy flow, the same sign of them indicating the energy flows from dark energy to dark matter while the different sign signaling the opposite. For what concerns the background dynamics, the evolution of the scalar field is described by the modified Klein Gordon equation via

$$\ddot{\phi} + 2\dot{H}\dot{\phi} + a^2 \frac{dV}{d\phi} = a^2 \frac{r}{1 - r\phi} \rho c.$$  

From the Einstein field equation we can get the Friedmann equation as follows

$$\mathcal{H}^2 = \frac{8\pi G}{3} a^2 \left( \rho_r + \rho_b + \rho_c + \frac{\dot{\phi}^2}{2a^2} + V(\phi) \right).$$

Here the relativistic component ‘r’ and the baryons ‘b’ are assumed to be uncoupled to the scalar field in this model, hence the evolutions of their energy densities still obey the standard conservation equations

$$\dot{\rho}_r + 4\mathcal{H}\rho_r = 0, \quad \dot{\rho}_b + 3\mathcal{H}\rho_b = 0.$$  

In the linear theory, equations of the first order perturbations for dark matter can be written as

$$\delta_c = -\theta_c - \frac{\dot{h}}{2} - \frac{r}{1 - r\phi} \dot{\phi} + \frac{r^2}{(1 - r\phi)^2} \ddot{\phi},$$

$$\dot{\theta}_c = -\mathcal{H}\theta_c + \frac{r}{1 - r\phi} \dot{\phi} - \frac{r^2}{1 - r\phi} \ddot{\phi},$$

where $\delta_c$ is the perturbed density contrast and $\theta_c = i k_j v_j^c$ is the gradient of velocity field for dark matter. The variable $\dot{h}$ is the trace part in the synchronous gauge metric perturbation. Perturbation in the scalar field $\phi \equiv \delta \phi$ evolves according to the perturbed Klein Gordon equation, which can be written as

$$\ddot{\phi} + 2\dot{H}\dot{\phi} + k^2 \phi + a^2 \frac{dV}{d\phi} \phi = \frac{\dot{h} \phi}{2}$$

$$= -a^2 \frac{r^2}{(1 - r\phi)^2} \phi c + a^2 \frac{r}{1 - r\phi} \rho_c \delta_c.$$  

For the other components, radiation and baryon, the perturbation equations follow from the Boltzmann equations, which are the same as those in the ΛCDM model.

**III. COSMOLOGICAL DATASETS**

We use the latest results of the CMB measurements from Planck 2015 [6] to derive constraints, which can be directly compared to the previous ones, for the Yukawa interaction model [29]. In our analysis, we take all the CMB temperature and polarization spectrum (TT, TE, EE, BB) except the BB power spectrum for which only the low-$\ell$, i.e. $2 < \ell < 30$, measurement is made available.

In addition to the Planck datasets, we also consider the weak gravitational lensing measurements from the Kilo Degree Survey [2]. The KiDS is designed to measure shapes of galaxies with photometric redshifts and it performs a study of weak lensing tomography. The lensing observables are given by the two point share correlation function $\xi_{ij}$ between two redshift bins $i$ and $j$ at the angular position $\theta$ on the sky, which can be expressed by the convergence power spectrum $P_{\kappa}^{ij}$ via

$$\xi_{ij}(\theta) = \frac{1}{2\pi} \int d\ell P_{\kappa}^{ij} J_0(\ell \theta),$$

where $l$ is the angular wave number, and $J_0(\ell \theta)$ is the zeroth (for $\xi_+$) or the fourth (for $\xi_-$) order Bessel functions of the first kind. Using the Limber approximation, the convergence power spectrum $P_{\kappa}^{ij}$ can be related to the matter power spectrum $P_{\delta}^{ij}$ via

$$P_{\kappa}^{ij} = \int_0^{\chi_H} d\chi \frac{W_i(\chi)W_j(\chi)}{\chi^2} \frac{P_{\delta}}{J_0^2} l \left( \frac{\chi}{\chi}, \chi' \right),$$

where $\chi$ is comoving radial distances and $\chi_H$ is the comoving distance evaluated at an infinite redshift. The lensing weighting function $W_i(\chi)$ is given by [32–34]

$$W_i(\chi) = \frac{3a(\chi)^2 H(\chi)^2 \Omega_m(\chi)}{2c^2} \chi \int_0^{\chi_H} d\chi' n_i(\chi') \frac{\chi'}{\chi'}.$$  

where $\Omega_m = \rho_m/\rho_{crit}$ with the critical density $\rho_{crit} = 3H^2/(8\pi G)$, $c$ is the speed of light, $n_i(\chi)d\chi$ is the effective number of galaxies in redshift bin $i$ within the range of $d\chi$ and it is normalized as $\int_0^{\chi_H} n_i(\chi) d\chi = 1$.

The KiDS datasets consist of four tomographic redshift bins between $z = 0.1$ to $z = 0.9$ with equal widths $\Delta z = 0.2$, and nine angular bins with central values at $\theta = [0.7134', 1.452', 2.956', 6.017', 12.25', 24.96', 50.75', 103.3', 210.3']$. For each tomographic redshift pair $(ij)$, the measurements cover seven angular bins smaller than $72'$ for $\xi_{ij}^+$ and six angular bins larger than $4.2'$ for $\xi_{ij}^-$, which means that the last two angular bins are marked out for $\xi_{ij}^+$ and the first three bins are marked out for $\xi_{ij}^-$. This equates to a total of 130 angular band powers in this datasets [2, 35].
In order to test the Yukawa interaction model, we implement the background and linear density perturbation equations as described in the previous section into the CAMB code [36], and then use a modified CosmoMC code package [1] which has already integrated the weak lensing module [35], to estimate the parameters that best describe the observational data. For the MCMC runs, we fix the effective number of neutrino species to $N_{\text{eff}} = 3.046$, the sum of neutrino masses to $\sum m_\nu = 0.06$ eV and the helium abundance to $Y_p = 0.24$. The convergence criterion is set to $R - 1 = 0.02$ where $R$ is the Gelman–Rubin threshold [37].

### IV. FITTING RESULTS

We consider a Yukawa interaction between two dark sectors and constrain this model by employing the most recent cosmological data including the CMB anisotropies from Planck 2015 and the weak gravitational lensing observations from KiDS. In our numerical analysis we have let the coupling parameter $r$ and the scalar potential parameter $\lambda$ to vary freely. The priors on the cosmological parameters are chosen the same as the ones in [29], listed in Table I, so that the comparisons can be carried out by using the Planck2013 results available in [29] and our new results from Planck2015, and also the concordance problem can be examined between the Planck datasets and the KiDS datasets.

**TABLE I: Priors on cosmological parameters**

| Parameter | Prior          |
|-----------|----------------|
| $\Omega_b h^2$ | [0.005,0.1]     |
| $\Omega_c h^2$ | [0.001,0.99]   |
| $100\theta$  | [0.5,10]       |
| $r$          | [0.01,0.8]     |
| $n_s$        | [0.9,1.1]      |
| $\log(10^{10} A_s)$ | [2.7,4]      |
| $\lambda$    | [0.1,1.5]      |
| $r = \frac{\lambda}{M_{\text{pl}}}$ | [-0.1,0.1] |

The constraints on the parameters and the best fit values are reported in Table II where we also include the previous results in [29]. Fig. 1 shows the 1D marginalized posterior distributions by using the Planck datasets, and the results from the KiDS datasets are shown in Fig. 2. The 2D distributions for some parameters of interest are plotted in Fig. 3. From these results, we find that Planck 2015 data produce a significant improvement in the constraints compared with the previous results by using Planck 2013 data. We can see that the 1σ range for the coupling parameter $r$ is much smaller and the best fit value of it becomes less negative by using the new Planck datasets. For the scalar potential parameter $\lambda$, the new Planck data has improved the 1σ range but it is still not enough to constrain this parameter as shown in Fig. 1. From Fig. 3 we find that the degeneracies between the parameters $\Omega_c h^2$, $\lambda$ and $r$ do not have any significant difference from the previous results obtained from Planck 2013.

Due to large band power uncertainties in the weak lensing measurements, the constraints from the KiDS data have wider 68% confidence regions compared to that from the Planck data, which is clearly shown in Fig. 2. Note that the amplitude of scalar perturbation $A_s$ and the scalar spectral index $n_s$ are mainly constrained by the priors rather than by the KiDS data. We find that the KiDS data presents a preference for larger values of the scalar potential parameter $\lambda$ than the Planck data, and the best fit values of the coupling parameter $r$ becomes positive which is opposite to the results obtained from Planck data. Besides, we also find that the best fit values we obtained for $\lambda$ and $r$ can help to alleviate the coincidence problem. As shown in Fig. 4, we present the time evolution of the ratio between the energy densities of dark matter and dark energy, we can see that the energy densities of dark matter and dark energy in the Yukawa interaction models have more time to be comparable in the past.

In this work we also aim to investigate whether the Yukawa interaction model can alleviate the tension between KiDS and Planck that has been reported for the $\Lambda$CDM model. Fig. 5 shows the parameter constraints in the $S_8-\Omega_m$ plane for the Yukawa interaction model and the standard $\Lambda$CDM model which has been presented in [34] Figure 1. We find that different from the $\Lambda$CDM model, the KiDS and Planck constraint contours of the Yukawa interaction model start to overlap with each other. In order to examine what level the tension between Planck 2015 and KiDS has been reduced by the Yukawa interaction model compared to the $\Lambda$CDM model, we define a tension parameter. Since current lensing data mainly constrain the $S_8$ parameter combination well, this parameter $T$ can be defined as [35]

$$T(S_8) = \frac{|\langle S_8^K \rangle - \langle S_8^P \rangle|}{\sqrt{\sigma^2(\langle S_8^K \rangle) + \sigma^2(\langle S_8^P \rangle)}},$$

where $S_8 = \sqrt{\Omega_m}$, $\langle S_8 \rangle$ is the mean value over the posterior distribution and $\sigma$ refers to the symmetric 68% confidence interval about the mean. The superscripts K denotes the KiDS data and P denotes the Planck 2015 data. The values of $T(S_8)$ between KiDS and Planck 2015 datasets for the $\Lambda$CDM and Yukawa interaction models is 2.11σ and 1.54σ, respectively. We can see that the Yukawa interaction model can reduce discordance and moderately alleviate the tension inferred from the standard $\Lambda$CDM model.

[1] https://github.com/sjoudaki/kids450
FIG. 1: 1D distributions for the cosmological parameters. The blue lines correspond to the Planck 2013 constraints, the red lines correspond to Planck 2015.
FIG. 2: 1D distributions for the cosmological parameters. The blue lines correspond to the Planck 2013 constraints, the red lines correspond to Planck 2015 and the gray lines correspond to KiDS.

FIG. 3: 2D distributions for selected parameters.
FIG. 4: Time evolution of the ratio between the energy densities of dark matter and dark energy. The dashed lines correspond to the Yukawa interaction model with different best fit values of $\lambda$ and $r$ listed in Table II, where the green line correspond to Planck 2013, the blue line correspond to Planck 2015 and the yellow one correspond to KiDS-450.

V. CONCLUSIONS

In this work we have obtained the observational constraints on the Yukawa-type dark matter and dark energy interaction model using both weak gravitational lensing data from the KiDS and the updated CMB data from Planck. We find that the constraints from Planck 2015 have been clearly improved compared with that from Planck 2013. And due to large band power uncertainties, the KiDS datasets alone have less constraining power than the Planck datasets. From the constraint results we find that an interaction between dark sectors is compatible with both datasets, where the Planck data induces evidence for a negative of the coupling parameter $r$, while the KiDS data present a preference for a positive value of $r$. The interaction in the Yukawa model can help to alleviate the coincidence problem, to accommodate longer period for dark matter and dark energy to be comparable to each other.

We also investigate whether the Yukawa interaction model can alleviate the $\Lambda$CDM discordance problem between KiDS and Planck datasets, and to what extent this model can relieve. Employing the tension parameter diagnostics, we find that the Yukawa interaction model can reduce discordance between these two datasets to $1.54\sigma$ and moderately alleviate the tension inferred from the standard $\Lambda$CDM model.

With the improvement of the weak lensing measurements, the desired concordance between weak lensing and CMB datasets can be used to support the interaction between dark sectors.

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