Testing interacting dark matter and dark energy model with cosmological data

Gong Cheng,1,2 Yin-Zhe Ma,3,4 Fengquan Wu,1 Jiajun Zhang,5 and Xuelei Chen1,2,6
1Key Laboratory of Computational Astrophysics, National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Beijing 100101, China
2School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China
3School of Chemistry and Physics, University of KwaZulu-Natal, Westville Campus, Private Bag X54001, Durban, South Africa
4NAOC-UKZN Computational Astrophysics Center (NUCAC), University of KwaZulu-Natal, Durban, 4000, South Africa
5Center for Theoretical Physics of the Universe, Institute for Basic Science (IBS), Daejeon, 34126, Korea
6Center for High Energy Physics, Peking University, Beijing 100871, China

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We investigate the model of dark matter-dark energy (DM-DE) interaction with coupling strength proportional to the multiplicity of dark sector densities with different power indices $Q = \gamma \rho_c^\alpha \rho_d^\beta$. We first investigate the modification of the cosmic expansion history, and then further develop the formalism to take into account the cosmological perturbations and dark matter temperature evolution. We then use the latest observational cosmology data, including cosmic microwave background (CMB) data, baryon acoustic oscillations (BAO) data, redshift-space distortion (RSD) data and Type Ia supernovae (SNe) data to constrain the model parameters. We find in the phantom region, a positive $\alpha$ is preferred by the data above $2\sigma$ statistic significance. If we choose the power indices to be integers or half-integers for plausible physics of particle interaction, the allowed values within $1\sigma$ confidence regions are $\alpha = 0.5$ and $\beta = 0, 0.5, 1$. The inclusion of BAO and RSD data from large-scale structure and SNe data improves the constraints significantly. Our model predicts lower values of $f(z)\sigma_8(z)$ at $z < 1$ comparing to $\Lambda$CDM model, which alleviates the tension of $\Lambda$CDM with various RSD data from optical galaxy surveys. Overall, the DM-DE interaction model is consistent with the current observational data, especially providing a better fit to the RSD data.

I. INTRODUCTION

Recently, the Planck measurement of the cosmic microwave background radiation (CMB) produces the best-fitting cosmological parameters, which are in good agreement with the low redshift observations (e.g., Baryon Acoustic Oscillation (BAO) from galaxy survey, Type Ia supernovae data (SNe) and galaxy lensing measurements) [1]. However, there is a roughly $2.5\sigma$ confidence level (C.L.) tension between the base Planck $\Lambda$CDM cosmology prediction and the DES combined-probe results (the later prefers a late-time clustering amplitude $\sigma_8$ or matter density $\Omega_m$). Besides, the Planck base $\Lambda$CDM cosmology requires $H_0 = (67.4 \pm 0.5)$ km s$^{-1}$ Mpc$^{-1}$, which leads to a $4.0\sigma - 5.8\sigma$ tension with the local Hubble constant measurements depending on the approaches used [2]. Many new observations of Hubble constant and new physics trying to explain the discrepancy are discussed in Ref. [2].

Theoretically, new ideas beyond $\Lambda$CDM model are developed, aiming to solve the well-known cosmological constant problem and coincidence problem. Moreover, it has been pointed out that the effective field theory that compatible with string theory should satisfy the swampland criteria, while the cosmological constant scenario does not [3].

One possible way to alleviate these problems is to consider the interaction between dark sectors [4]. It is reported that the $H_0$ and $\sigma_8$ tension could be solved or reduced simultaneously by considering an interaction in the dark sector [5, 6]. Also, it could alleviate the coincidence problem by allowing a constant ratio of dark sector densities [7]. In Ref. [8], the authors explore the possibility that the interaction functions possess a minimum and argue that this model could alleviate the tension between the swampland conjectures and the quintessential potential [8]. Besides, in the framework of field theory, it is natural and inevitable to consider such interactions between dark sectors, and the investigation of the interaction could help us to understand the nature of them [9].

Various models are proposed and tested in the literature (for reviews, see [10, 12]). A much studied case is $Q = H(\xi_1\rho_c + \xi_2\rho_d)$. Other models are also considered, such as $Q = \Gamma(\rho_c + \rho_d)$ [13], $Q = HT\rho_c\rho_d/(\rho_c + \rho_d)$ [14], where $\rho_c$ and $\rho_d$ are the energy densities of dark matter and dark energy respectively and $\Gamma, \xi_1, \xi_2$ describe the interaction strength. Besides, the holographic principle is applied in some work [11, 14] and the coupled quintessence model is discussed in Ref. [10].

However, a physically more plausible form of interaction form is for the interaction term to be proportional to the product of the densities of interacting components or some powers of these [15, 17]. For example, in the familiar case of chemical reactions this is the case. Thus a natural way to construct the phenomenological model is to suppose the interaction term is proportional to some $Q = f(\rho_c, \rho_d)$, where $f$ is a function of the dark sector densities.

In this paper, we pay attention to the flexible interaction model with coupling strength formed by a power index as $Q = \gamma \rho_c^\alpha \rho_d^\beta$. This model is naturally consistent with the observed cosmic expansion history, and allows a constant ratio of dark sector densities $Q = \gamma \rho_c^\alpha \rho_d^\beta$. We test the model with the latest observational cosmology data, including cosmic microwave background (CMB) data, baryon acoustic oscillations (BAO) data, redshift-space distortion (RSD) data and Type Ia supernovae (SNe) data to constrain the model parameters. We find in the phantom region, a positive $\alpha$ is preferred by the data above $2\sigma$ statistic significance. If we choose the power indices to be integers or half-integers for plausible physics of particle interaction, the allowed values within $1\sigma$ confidence regions are $\alpha = 0.5$ and $\beta = 0, 0.5, 1$. The inclusion of BAO and RSD data from large-scale structure and SNe data improves the constraints significantly. Our model predicts lower values of $f(z)\sigma_8(z)$ at $z < 1$ comparing to $\Lambda$CDM model, which alleviates the tension of $\Lambda$CDM with various RSD data from optical galaxy surveys. Overall, the DM-DE interaction model is consistent with the current observational data, especially providing a better fit to the RSD data.
powers of the densities,
\begin{align}
\dot{\rho}_c + 3aH\rho_c &= a\gamma\rho_c^\alpha\rho_d^\beta, \quad (1) \\
\dot{\rho}_d + 3a(1 + w)H\rho_d &= -a\gamma\rho_c^\alpha\rho_d^\beta, \quad (2)
\end{align}
where the dot denotes the time derivative with respect to the conformal time and \( a \) is the scale factor. In this work, we consider a minimal model in which the equation of state of dark energy \( w \) is a constant. The power index \( \alpha, \beta \) are assumed to be non-negative numbers. If we set the indices to be simple integers, the model could reduce to the interactions in the usual sense, such as "decay" (if one is 0 and the other is 1), "annihilation" (if one is 0, and the other is 2). And \( \gamma > 0 \) indicates dark energy is converted to dark matter, while \( \gamma < 0 \) indicates the opposite process.

Previous work on the interacting dark energy models mainly focuses on the impact on the background evolutions and expansion history. However, from the theoretical point of view, the inhomogeneity of dark matter will naturally lead to dark energy perturbations as the energy transfers between the two components. And the change of density and velocity perturbations will influence the structure formation and some observational effects (e.g., redshift space distortion). So in this paper, we also investigate the impact on the growth of cosmological perturbations.

Notably, as the perturbed interaction four-vector \( \delta Q^\nu \) cannot be uniquely determined by the background interaction form \( Q \), the formalisms developed by different groups differ from each others slightly. In Refs. [18–21], \( \delta Q^\nu = \delta Q u^\nu_{\lambda}/a \) or \( \delta Q^\nu = \delta Q u^\nu_{\lambda}/a \) is assumed to avoid momentum transfer in the rest frame of dark sector, where \( u^\nu_{\lambda} \) and \( u^\nu_{\lambda} \) are the four velocities. In Refs. [9, 21], on the other hand, the authors assume the energy transfer is stationary and non-gravitational interaction between dark sectors does not exist and so the non-vanishing component is \( \delta Q^0 = \delta Q/a \). We regard the later assumption as a more natural choice and follow it to develop the formalisms in our model.

\section{II. Formalisms}

In this section, we present the formalisms of background evolutions, linear perturbations and thermodynamics in this model. The background evolutions of dark matter and dark energy are described by Eqs. (1) and (2). Due to the energy transfer, the energy-momentum tensor of each component \( (\lambda = c, d) \) is no longer conserved,
\begin{equation}
\nabla^\mu T^\mu_{\lambda}(\lambda) = Q^\lambda_{\nu}(\lambda), \quad (3)
\end{equation}
\begin{equation}
Q = aQ^0_c = -aQ^0_c = \gamma\rho_c^\alpha\rho_d^\beta, \quad (4)
\end{equation}
where \( Q \) is the energy transfer rate with respect to the cosmic time and the spatial component \( Q^1(\lambda) \) is zero in the background level. For convenience, we use the critical density today to define the dimensionless interaction parameter as
\begin{equation}
\lambda = \gamma\rho_c^{\alpha+\beta-1}H_0^{-1}, \quad \rho_c = 3H_0^2M^2_\text{pl}. \quad (5)
\end{equation}

For the linear perturbations in the presence of the interaction, we first review the formalisms developed in Refs. [9, 21, 22], and then apply them in this model. Assuming that there is no non-gravitational interaction between dark energy and dark matter, and the energy transfer is stationary, the perturbed four-vector in the synchronous gauge is,
\begin{align}
\delta Q^0_c &= \frac{1}{a}\delta Q, \quad (6) \\
\delta Q^{i}_{p(\lambda)} &= Q^{i}_{p(\lambda)}|_{\text{d}} + Q^{0}_{p(\lambda)}v^{i}_{\text{t}} = 0. \quad (7)
\end{align}
\( \delta Q^{i}_{(\lambda)} \) is the potential of \( \delta Q^{i}_{p(\lambda)} \). \( Q^{i}_{p(\lambda)}|_{\text{d}} \) denotes the external non-gravitational force density between the two components and \( v^{i}_{\text{t}} \) is the energy transfer velocity. Based on this formalism, we obtain the density and velocity perturbation equations for dark matter and dark energy in our model,
\begin{align}
\dot{\delta}_c &= -(\theta_c + \frac{\dot{h}}{2}) + a\gamma\rho_c^{\alpha-1}\rho_d^{\beta}(\alpha - 1)\delta_c + \beta\delta_d, \quad (8) \\
\dot{\theta}_c &= -aH\theta_c - a\gamma\rho_c^{\alpha-1}\rho_d^{\beta}\delta_c + k^2\omega^2\delta_c, \quad (9) \\
\dot{\delta}_d &= -(1 + \omega)(\theta_d + \frac{\dot{h}}{2}) + 3aH(\omega - c^2_\omega)\delta_d \\
&-a\gamma\rho_c^{\alpha-1}\rho_d^{\beta-1}[\beta(\beta - 1)\delta_d + \alpha\delta_c] - 3aH \\
&(c^2_\omega - c^2_\omega)3aH(1 + \omega) + a\gamma\rho_c^{\alpha-1}\rho_d^{\beta-1}\theta_d \quad (10) \\
\dot{\theta}_d &= -aH\theta_d(1 - 3c^2_\omega) - \frac{\dot{h}^2}{1 + w}\theta_d + \frac{1}{1 + w} \\
&(1 + c^2_\omega)a\gamma\rho_c^{\alpha-1}\rho_d^{\beta-1}\theta_d + \frac{k^4\omega^2\delta_d}{1 + w}, \quad (11)
\end{align}
where we have used the form of the perturbed pressure of dark energy in a general frame [9, 23],
\begin{equation}
\delta P_d = c^2_d\rho_d + (c^2_\omega - c^2_d)\frac{3aH(1 + \omega)\theta_d\rho_d - a^2Q^0_d\theta_d}{k^2}. \quad (12)
\end{equation}
In practice, we set the effective sound speed of dark energy in the rest frame \( c_e = 1 \) and adiabatic sound speed of dark energy \( c^2_a = w \). We set the adiabatic initial conditions for the perturbations following [24]. In order to obtain analytical solutions of initial conditions, we neglect all the interaction terms when solving the continuity and Euler equations.
So our initial conditions are identical with Ref. [24].

\[
\begin{align*}
\delta_c &= \frac{3}{4} \delta_\gamma = -\frac{1}{2} C(k\tau)^2, \\
\theta_c &= 0, \\
\theta_\gamma &= -\frac{1}{18} C(k^4\tau^3), \\
\delta_d &= -\frac{C}{2}(1 + w) \frac{4 - 3c^2_e}{4 - 6w + 3c^2_e}(k\tau)^2 \\
&= 1 + w \frac{7 - 6w}{7 - 6w} \delta_c, \\
\theta_d &= -\frac{C}{2} \frac{c^2_e}{4 - 6w + 3c^2_e}(k\tau)^3 \frac{k}{c} = \frac{9}{7 - 6w} \theta_\gamma,
\end{align*}
\]

where \(\gamma\) corresponds to photons and \(C\) is a constant.

Besides, the term \(k^2c^2_e\delta_c\) appearing in the RHS of \(\theta_c\) is always ignored by previous work. Nevertheless, compared with \(\Lambda\)CDM model, \(\delta_c\) and \(c_e\) are affected by the interaction. Hence this term might be enhanced and should be taken into account. It’s necessary to investigate the contribution of this term to \(\theta_c\). The sound speed of dark matter \(c_e\) is defined as [22]

\[
c^2_e = \frac{k_B T_c}{m_c} \left(1 - \frac{d \ln T_c}{3d \ln a}\right),
\]

where \(m_c\) is the mass of dark matter particle. We follow the methods in Refs. [23, 24] to calculate the temperature evolution of dark matter in the interacting model using the second law of thermodynamics and obtain

\[
\begin{align*}
\dot{T}_c &= \left(\frac{\partial T_c}{\partial n_c}\right)_{\rho_c} n_c + \left(\frac{\partial T_c}{\partial \rho_c}\right)_{n_c} \rho_c \\
&= \left(\frac{\partial T_c}{\partial n_c}\right)_{\rho_c} \left(-3aH n_c + aQ / m_c\right) \\
&\quad + \left(\frac{\partial T_c}{\partial \rho_c}\right)_{n_c} \left(-3aH \rho_c + aQ\right) \\
&= -2aH T_c \left(1 - \frac{\gamma \rho^2}{3H^2}\right),
\end{align*}
\]

where we have used \(T \left(\frac{\partial n}{\partial \rho}\right)_{n} = (\rho + p) \left(\frac{\partial T}{\partial \rho}\right)_{n} + n \left(\frac{\partial T}{\partial m}\right)\rho\), \(\left(\frac{\partial \rho}{\partial \rho_c}\right)_{n_c} = 2/3\) and \(n\) is the number density. As the wrong relation \(\left(\frac{\partial \rho}{\partial \rho_c}\right)_{n_c} = \frac{w_{\text{eff}} - w_c - 3H \rho}{3H \rho_c}\) is used in Ref. [24], Eq. (34) in Ref. [24] is related to Eq. (19) in this paper by a factor 2/3.

To solve the above equation numerically, we need to set the initial temperature in the early universe. If we assume \(T_c = 0\) initially, we obtain a trivial solution, as the macroscopic interaction of the dark matter does not generate the microscopic motion and temperature. Here we set the initial temperature as evolved from earlier time, assuming that dark matter annihilates to baryons through weak-scale interactions at high energies [27],

\[
T_c(z) = T_b(z) \quad \text{at} \quad H(z) = \langle \sigma_{\text{w}v} \rangle \rho_c(z) / m_c,
\]

where we take the weak-scale cross section \(\langle \sigma_{\text{w}v} \rangle \sim 10^{-26} \text{cm}^2 \text{s}^{-1}\) and \(T_b\) is the baryons temperature.

| Redshift | Measurement | Value | Surveys |
|----------|-------------|-------|---------|
| 0.106    | \(r_s/D_{\nu}\) | 0.327 ± 0.015 | 6dFGS [34] |
| 0.15     | \(D_{\nu}/r_s\) | 4.47 ± 0.16 | SDSS DR7-MGS [35] |
| 0.35     | \(D_{\nu}/r_s\) | 9.11 ± 0.33 | SDSS DR7-LRG [36] |
| 0.38     | \(D_{\delta}(r_s,\bar{n}_s)/r_s\) | 1518.4 ± 22.4 | SDSS DR12-BOSS [37] |
| 0.38     | \(H(z)(r_s,\bar{n}_s)\) | 81.51 ± 1.91 | SDSS DR12-BOSS |
| 0.51     | \(D_{\delta}(r_s,\bar{n}_s)/r_s\) | 1977.4 ± 26.5 | SDSS DR12-BOSS |
| 0.51     | \(H(z)(r_s,\bar{n}_s)\) | 90.45 ± 1.94 | SDSS DR12-BOSS |
| 0.61     | \(D_{\delta}(r_s,\bar{n}_s)/r_s\) | 2283.2 ± 31.9 | SDSS DR12-BOSS |
| 0.61     | \(H(z)(r_s,\bar{n}_s)\) | 97.26 ± 2.09 | SDSS DR12-BOSS |
| 1.52     | \(D_{\nu}/r_s\) | 26.005 ± 0.995 | SDSS DR14 [38] |

TABLE I: BAO measurements from various surveys adopted in this work.

\[
D_{\nu}(z) = \left[D_{\delta}(z) \frac{c_s^2}{H(z)}\right]^{1/3},
\]

\(r_s\) is the comoving sound horizon at the end of the baryon drag epoch.

The peculiar velocity of galaxies could lead to distortion of clustering of galaxies in the redshift space. So measuring RSD effect can help us to probe the growth function. Table II shows the constraints on \(f(z)\sigma_8(z)\).
from various surveys. The scale-independent growth function is defined as

$$f(z) = \frac{d \ln D}{d \ln a} = \frac{\delta(a)}{\delta(a_0)}.$$ (22)

We use the SNe data from the “Pantheon Sample”, which consists of 1048 SNe with the redshift spanning $0.01 < z < 2.3$. This sample is a combination of SNe Ia from Pan-STARRS1 Medium Deep Survey, SNLS, and several low-z and Hubble Space Telescope samples [18].

Due to the divergency of perturbations when $w$ approaches $-1$, we constrain the models with $w < -1$ and $w > -1$ separately. And for generality, we choose a broad range for the dark matter mass $m_c$. The prior ranges are set as

$$\alpha > 0,$$ (23)
$$\beta > 0,$$ (24)
$$-2 < w < -1 \text{ or } -1 < w < -0.5,$$ (25)
$$1 \text{ eV} < m_c < 10 \text{ TeV}.$$ (26)

**IV. RESULTS AND DISCUSSIONS**

Fig. 1 shows the confidence contours for the parameters in the models $w < -1$ and $w > -1$. Tables II and IV summarize the best-fit parameters and 1 $\sigma$, 2 $\sigma$ bounds from the CMB data and CMB+BAO+RSD+SNe dataset. We find the constraints for the two models $w < -1$ and $w > -1$ differ from each other significantly.

For the model $w < -1$, $\lambda \in (-0.05, 0.21)$ at 95% confidence level, indicating the deviation from $\Lambda$CDM model cannot be too large. And $\alpha \in (0.03, 0.63)$, $\beta \in (0.3, 6)$, $w \in (-1.072, -1)$ at 95% confidence level imply that a non-zero value of $\alpha$ is preferred by the dataset. If we limit the power indices to integers or half-integers for physical reasons, then the preferred values are $\alpha = 0.5$ and $\beta = 0, 0.5, 1$. The inclusion of large-scale structure (LSS) and SNe data improves the constraints of $\Lambda$ significantly but has little impact on the other parameters.

For the model $w > -1$, we do not show the confidence regions of $\lambda$, because it can be very large to several hundred and could not converge. The 2$\sigma$ confidence regions for the other parameters are $\alpha \in (0, 0.32)$, $\beta \in (20, 43)$ and $w \in (-0.9957, -0.9835)$. Thus a non-zero and large value of $\beta$ is preferred by the data. In addition, $w$ obeys a nearly Gaussian distribution, peaking at $-0.99$. In this model, the viable parameter space is reduced by about 50% after including the LSS and SNe data.

In the following part, we take the best-fitting models as examples to discuss the background, perturbations and thermodynamics evolutions in the existence of interaction. In both best-fitting models, $\lambda$ is positive, suggesting dark energy is converted to dark matter. Fig. 2 shows the evolutions of densities for dark matter and dark energy, compared with the $\Lambda$CDM model. To quantify the contribution of interaction to the density evolution, we compare the interaction term with expansion term in Fig. 3. The contribution of interaction increases with cosmic time and reaches the maximum at redshift $z \sim 1$. In the $w < -1$ model, the density of dark matter is enhanced by several percentage from $z \sim 1$ to the present day and the density of dark energy at $z = 10^4$ is about 30% of the present day value.

In the $w > -1$ model, a large $\beta$ is favoured. So the interaction term $a\rho_c^\beta\rho^\beta_\Lambda = aH_0\rho_c\lambda(\rho_c/\rho_\Lambda)^\alpha(\rho_\Lambda/\rho_c)^\beta$ is negligible compared to the expansion terms. The density evolution of dark matter is nearly identical with $\Lambda$CDM model and the density evolution of dark energy is dominated by the equation of state $w$. Because the contributions of the interaction term to the background and perturbations evolutions are small, varying $\lambda$ has little impact on the observables. So the data is insensitive to the variation of $\lambda$, and a convergent constraint for this parameter cannot be obtained in this model.

The cosmological perturbations are shown in Fig. 4. We only plot the density perturbation of dark matter in the $\Lambda$CDM model, while the evolution in the interacting model could have several percent deviation. For the dark energy, the density perturbation which is several orders smaller than $\delta_a$ grows and then keeps stable since $z \sim 10^4$. In the $\Lambda$CDM model, one usually sets $\theta_c = 0$ in the synchronous gauge. In the interacting models, $\theta_c$ has a tiny value. However, for dark energy, $\theta_a$ is extremely large, even several orders larger than $\theta_c$. We note that to calculate $\theta_c$, the term $k^2\delta_a^2$ is in the same order of $aH_0\theta_c$ and even dominates in the range $0 < z < 10^4$ and $0.01 \text{ Mpc}^{-1} < k < 1 \text{ Mpc}^{-1}$. So this term cannot be dropped. But $\theta_a$ is really small and hence different choices of $m_c$ have little impact on the evolution of the universe. We plot the posterior distribution of $m_c$ in Fig. 5 and the distribution is nearly flat within the range 1 keV–1 TeV. The temperature evolutions of dark matter are shown in Fig. 6. Dark matter cools nearly adiabatically until $z \sim 1$ and the temperature is enhanced due
FIG. 1: One-dimensional marginalized posterior distribution and 68%, 95% confidence regions of the four free parameters in the model. The red lines correspond to the constraining results from CMB data only, and the blue lines correspond to joint constraints from CMB+BAO+RSD+SNe dataset. Left panel is for the model \( w < -1 \) and the right panel is for \( w > -1 \).

### TABLE III: Constraints on the parameters in the model \( w < -1 \).

| Parameter | Planck 68% C.L. | Planck 95% C.L. | Planck+BAO+RSD+SNe 68% C.L. | Planck+BAO+RSD+SNe 95% C.L. | Best fit |
|-----------|----------------|----------------|-----------------------------|-----------------------------|----------|
| \( \lambda \) | \( 0.27^{+0.47}_{-0.29} \) | \( 0.60^{+0.31}_{-0.07} \) | \( 0.06^{+0.15}_{-0.11} \) | \( 0.50 \) |
| \( \alpha \) | \( 0.32^{+0.26}_{-0.13} \) | \( 0.37^{+0.25}_{-0.11} \) | \( 0.37^{+0.26}_{-0.34} \) | \( 0.22 \) |
| \( \beta \) | \( 0.80^{+1.3}_{-0.76} \) | \( 1.19^{+1.1}_{-1.19} \) | \( 1.2^{+2.4}_{-1.2} \) | \( 1.09 \) |
| \( w \) | \( -1.03^{+0.034}_{-0.011} \) | \( -1.029^{+0.029}_{-0.010} \) | \( -1.029^{+0.029}_{-0.043} \) | \( -1.047 \) |

### TABLE IV: Constraints on the parameters in the model \( w > -1 \).

| Parameter | Planck 68% C.L. | Planck 95% C.L. | Planck+BAO+RSD+SNe 68% C.L. | Planck+BAO+RSD+SNe 95% C.L. | Best fit |
|-----------|----------------|----------------|-----------------------------|-----------------------------|----------|
| \( \alpha \) | \( 0.157^{+0.22}_{-0.16} \) | \( 0.135^{+0.040}_{-0.013} \) | \( 0.13^{+0.19}_{-0.13} \) | \( 0.031 \) |
| \( \beta \) | \( 24^{+17}_{-11} \) | \( 31.8^{+0.1}_{-1.7} \) | \( 32^{+11}_{-12} \) | \( 34.6 \) |
| \( w \) | \( -0.9869^{+0.016}_{-0.0011} \) | \( -0.9901^{+0.0021}_{-0.0041} \) | \( -0.9901^{+0.0066}_{-0.0056} \) | \( -0.9910 \) |

to the interaction by about 2% in the \( w < -1 \) model. According to Eq. (19), if \( \gamma > 0 \) dark matter is heated by dark energy and otherwise cooled.

The linear matter power spectrum at present is shown in Fig. 7. As illustrated in Fig. 4 the dark matter perturbations in the interacting model is similar with \( \Lambda \)CDM model. So the linear power spectrum makes little difference. The modification to the nonlinear power spectrum is much more significant and we will discuss it in the future paper.

We plot the evolutions of \( f(z)\sigma_8(z) \) in our model and \( \Lambda \)CDM model in Fig. 8. \( f\sigma_8 = \alpha d\sigma_8(z)/da \) reveals the time derivative of matter fluctuations on the scale 8 \( h^{-1}\)Mpc. Most measurements of \( f(z)\sigma_8(z) \) at \( z < 1 \)
are lower than that predicted by ΛCDM model. Coincidentally, as discussed above, the interaction mainly influences the late time evolution of the universe (roughly \(z < 1\)). In the \(w < -1\) model, the evolution of \(f(z)\sigma_8(z)\) is similar with ΛCDM model at high redshift and decreases since \(z < 1\). So the fit to data points in our model is much better than the ΛCDM model, alleviating the tension at low redshift. Quantitatively, we calculate the reduced chi-square \(\chi^2 = \chi^2/(n - m)\) to obtain the goodness of fit, where \(n\) is the number of data points and \(m\) is the number of free parameters. We fix the cosmological parameters in different models and hence there are 5 free parameters left. So \(\chi^2\) is 0.56 for the \(w < -1\) model and 0.75 for the ΛCDM model. Also, the curve predicted by the \(w < -1\) model is within all the 1σ bounds of the measurements used in this plot.

V. SUMMARY

In this paper, we consider the possible interaction between dark matter and dark energy and the impact on the evolution of universe. The interaction strength is proportional to some powers of the densities. We follow some previous work to derive the equations governing the evolutions of perturbations and thermodynamics in this model. And then we constrain the model using the latest cosmological data with the modified Boltzmann code.

For the \(w > -1\) model, the data is insensitive to the variation of \(\lambda\), and the 2σ bounds are \(\alpha \in (0, 0.32), \beta \in (20, 43), w \in (-0.9957, -0.9835)\). A very large value of \(\beta\) is preferred by the data and \(w\) obeys the Gaussian distribution, peaking at \(-0.99\).

For the \(w < -1\) model, the constraining results are \(\lambda \in (-0.05, 0.21), \alpha \in (0.03, 0.63), \beta \in (0, 3.6)\) and \(w \in (-1.072, -1)\) at 95% confidence level. While the non-interacting case \((\lambda = 0)\) could accommodate the current data, a positive \(\alpha\) is preferred, indicating the coupling strength between dark sectors may depend on \(\rho_c^2\). For the physical reasons, one can choose the indices as integers or half-integers and the allowed values within 1σ regions are \(\alpha = 0.5\) and \(\beta = 0, 0.5, 1\). The inclusion of LSS and SNe data improves the constraints of some parameters significantly.

The background density evolution of dark matter could deviate from ΛCDM model by several percent. We also consider the perturbations in the existence of interaction and the impact on the structure formation and redshift space distortion. The density perturbation of dark matter could have deviation from ΛCDM model by several

FIG. 2: The ratio of densities in the interacting models and ΛCDM model for dark matter (left panel) and dark energy (right panel) with respect to the redshift \(z\). We choose the best-fitting models preferred by the CMB+BAO+RSD+SNe data set for the models \(w < -1\) and \(w > -1\).

FIG. 3: The ratio of interaction term \(a\gamma\rho_c^p\rho_\beta^d\) and expansion term \(3aH\rho_c\) for dark matter \((3a(1 + w)H\rho_d\) for dark energy\) in the same best-fitting models as Fig. 2.
percent. Notably, $\theta_d$ is several orders larger than the velocity perturbation of baryons $\theta_b$. We note that the term $k^2 c_s^2 \delta_c$ is dominant when calculating $\theta_c$ and hence could not be dropped. Because the velocity perturbation of dark matter is tiny, different choices of dark matter mass could hardly influence the results. In the $w < -1$ model, dark matter cools adiabatically, then heated due to the interaction by about 2% since $z \sim 1$.

The linear power spectrum in this model makes little difference and we will discuss the nonlinear power spectrum in the future paper. The observed $f(z)\sigma_8(z)$ values at $z < 1$ are mostly lower than that predicted by the $\Lambda$CDM model. As the effects of the interaction mainly appear at low redshift, the $w < -1$ model can alleviate the tension and fit the data points much better. Quantitatively, the reduced chi-square is 0.56 for the $w < -1$ model and 0.75 for the $\Lambda$CDM model. In summary, this class of interacting model in the phantom region ($w < -1$) is physically plausible and could provide better fit to the current CMB data from Planck, BAO and RSD data from SDSS and Type-Ia supernovae from Pantheon samples.

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FIG. 6: Left panel: Temperature evolutions of baryons and dark matter in the best-fitting models as Fig. 2. Right panel: The ratio of temperature exactly evolved as Eq. (19) and the temperature in the case without coupling (cooling adiabatically) under the same initial condition.

FIG. 7: Top panel: Linear matter power spectrum at $z = 0$ in the best-fitting models as Fig. 2. Bottom panel: The relative difference of matter power spectrum in the interacting model and $\Lambda$CDM model.

FIG. 8: $f(z)\sigma_8(z)$ evolutions with respect to the redshift in the best-fitting models as Fig. 2 and $\Lambda$CDM model. The data points with error bar are measurements from the surveys listed in Table II. We shift some of the data point horizontally a bit ($\Delta z < 0.003$) to avoid overlap.

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