ЖУРНАЛ ФІЗИЧНИХ ДОСЛІДЖЕНЬ
т. 28, № 1 (2024) 1903(6 с.)

JOURNAL OF PHYSICAL STUDIES
v. 28, No. 1 (2024) 1903(6 p.)

# CONSTRAINTS ON THE INTERACTION OF QUINTESSENCE DARK ENERGY WITH DARK MATTER AND THE EVOLUTION OF ITS EQUATION OF STATE PARAMETER

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(Received 05 December 2023; accepted 18 December 2023; published online 26 March 2024)

The paper discusses the cosmological model with an interaction between dynamical quintessence dark energy and cold dark matter. Evolution of the dark energy equation of state parameter is defined by the dark energy adiabatic sound speed and the dark sector interaction parameter, which must be a more physically correct model then the one previously used, in which this evolution was determined by some fixed dependence on the scale factor. The constraints on the interaction parameter and other parameters of the model were obtained using the cosmic microwave background, baryon acoustic oscillations and the supernova SN Ia data.

**Key words:** interacting dark energy, dark matter, cosmological perturbations.

DOI: https://doi.org/10.30970/jps.28.1903

## I. INTRODUCTION

The ΛCDM model is the simplest cosmological model which is in a very good agreement with astrophysical observational data. However, the theoretical explanation of this model is very problematic from the quantum-field theoretical point of view, which is described in reviews [1, 2]. The alternative to Λ term in Einstein's equations is the new component — dark energy (DE), which in most cosmological calculations is described as a perfect fluid with positive energy density and negative pressure, which causes accelerated expansion of the universe at present time. Such component can be easier to explain theoretically: it can be for example, some classical scalar field. The constraints on the equation of state parameter (EoS parameter) of DE, which in the simplest models is constant, point to the EoS parameter value close to $-1$ (which is ΛCDM model) [3]. And, when considering the more general models of dynamical DE (in them the EoS parameter varies with the expansion of the universe), their parameters constraints also prefer the ΛCDM model [3]. So they do not have any advantage in the explanation of the accelerated expansion of the universe [4, 5]. That is why there is a need to consider more complicated models of dynamical DE which could have a good theoretical explanation. Among such models are those, in which dynamical DE non-gravitationally interacts with cold dark matter (DM), which are called dynamical interacting dark energy models (dynamical IDE). This generalization is natural, because there are no known free fields in particle physics. These IDE models with the constant or variable EoS parameter were studied in detail for various forms of interaction term in works, some of which are [6–14]. They are also a promising solution to the $H_0$ and cosmic shear tensions in modern cosmology [15, 16]. Anyway the previously studied dynamical IDE models [17, 18] have the problem of the DE EoS parameter dependence on the universe's expansion being physically non-realistic. It is given by some fixed dependence on the scale factor, as for instance in [19–21]. So we consider the model of dynamical IDE, in which the evolution of the EoS parameter depends on internal properties of IDE. This evolution is parametrized by adiabatic sound speed of DE and a coupling parameter of DE–DM interaction [22, 23]. Also, we consider the most widely used type of the DE–DM interaction term, proportional to the energy density of DE [15, 24, 25]. The problem with such types of interaction used in earlier works is that they are not general-covariant. Hence, the general-covariant DE–DM interaction term [30] is used in our model of dynamical IDE. In this work, for the first time the constraints on the parameters of such model were obtained using the Markov Chain Monte Carlo sampling method. It must be noted that here the parameters of the model are restricted to values where DE is quintessential. The model was compared with the cosmic microwave background (CMB), baryon acoustic oscillations (BAO) and supernova of type Ia (SN Ia) observational data.

This paper is organized as follows: in Section II the general description of the model is given; in Section III, the observational data and the analysis method, used in this work are described; and in Section IV, the obtained results are discussed.

## II. MODEL OF THE DYNAMICAL IDE

The description of dynamical IDE and all other components of the universe is made in perfect fluid approximation with the stress-energy tensor:

$$T_i^k = (\rho + p)u_i u^k - p\delta_i^k \,. \qquad (1)$$

The universe is considered homogeneous and isotropic with zero spatial curvature, relative to which small perturbations of metrics and the stress-energy tensor of each component occur (perturbations are given in synchronous gauge):

$$ds^2 = a^2(\eta)[d\eta^2 - (\delta_{\alpha\beta} + h_{\alpha\beta})dx^\alpha dx^\beta], \qquad (2)$$

$$\begin{aligned}
\bar{T}_0^0 + \delta T_0^0 &= \bar{\rho} + \bar{\rho}\delta, \\
\bar{T}_0^\alpha + \delta T_0^\alpha &= 0 + (\bar{\rho} + \bar{p})v^\alpha, \\
\bar{T}_\alpha^0 + \delta T_\alpha^0 &= 0 - (\bar{\rho} + \bar{p})v^\alpha, \qquad (3) \\
\bar{T}_\alpha^\beta + \delta T_\alpha^\beta &= -\bar{p}\delta_\alpha^\beta - \delta p \delta_\alpha^\beta.
\end{aligned}$$

Here $a$ denotes a scale factor, $\eta$ is conformal time, $h_{\alpha\beta}$ is the perturbation of the metric tensor, $\bar{\rho}$, $\bar{p}$ are background energy density and pressure, $v^\alpha \equiv \mathbf{v} \equiv dx^\alpha/d\eta$ is the peculiar velocity, $\delta$ is the perturbation of density relative to its background value, $\delta p$ is the perturbation of pressure.

The sum of stress-energy tensors of dark components satisfy the general-covariant conservation equation, but separately, due to DE–DM interaction, they do not conserve:

$$T^k_{(\mathrm{de})i;k} = J_{(\mathrm{de})i}, \qquad (4a)$$

$$T^k_{(\mathrm{c})i;k} = J_{(\mathrm{c})i}. \qquad (4b)$$

Here $J_i$ is the DE–DM interaction term, ";" is a covariant derivative. From the conservation of the total stress-energy tensor of dark components follows that $J_{(\mathrm{c})i} = -J_{(\mathrm{de})i} = J_i$. There are many forms of the interaction term in works on IDE, but in this work one of the most often used is considered: its background zero component $\bar{J}_0$ is proportional to the energy density of DE [15, 24, 25]:

$$\bar{J}_0 = 3\beta a H \bar{\rho}_{\mathrm{de}}\,. \qquad (5)$$

Here $\beta$ is the interaction parameter, $H \equiv (da/d\eta)/a^2$ is the Hubble parameter. This interaction form is popular because of the absence of DE perturbations' non-adiabatic instabilities in the radiation-dominated epoch of the universe [24, 25]. Other forms of the DE–DM interaction for which DE perturbations are stable were studied in work [26]. The background component of the equations (4) with this interaction takes the following form:

$$\dot{\bar{\rho}}_{\mathrm{de}} + 3aH(1+w)\bar{\rho}_{\mathrm{de}} = -3\beta a H \bar{\rho}_{\mathrm{de}}, \qquad (6a)$$

$$\dot{\bar{\rho}}_{\mathrm{c}} + 3aH\bar{\rho}_{\mathrm{c}} = 3\beta a H \bar{\rho}_{\mathrm{de}}, \qquad (6b)$$

where the dot over $\bar{\rho}$ denotes its derivative on conformal time $\eta$ and $w$ is the DE EoS parameter. In this work, $w$ varies with the expansion of the universe, hence the DE is dynamical. There are several parametrizations of $w$ evolution proposed in [19–21]. In them, EoS parameter is given as some function of scale factor $a$ which does not depend on the internal properties of DE. But it is obvious that the evolution of $w$ must depend on them, and in the case of our IDE model, on the DE–DM interaction. To parametrize the evolution of $w$, which would satisfy these requirements, let us use adiabatic sound speed of DE. It is defined as $c_{\mathrm{a}}^2 = \dot{p}_{\mathrm{de}}/\dot{\rho}_{\mathrm{de}}$. Then from equation (6a) one can obtain the general equation for the evolution of $w$:

$$\frac{dw}{da} = \frac{3}{a}(1 + w + \beta)(w - c_{\mathrm{a}}^2)\,. \qquad (7)$$

In a general case, $c_{\mathrm{a}}^2$ is dependent on time, but in this work only the phenomenological models of IDE are considered for which $c_{\mathrm{a}}^2 = \mathrm{const}$ [22, 23]. Such model of DE for a non-interacting case was considered in [27–29]. The general solution of the system of equations (6), (7) was obtained and analyzed in detail in work [22], and has the following form:

$$w = \frac{(1 + c_{\mathrm{a}}^2 + \beta)(1 + w_0 + \beta)}{1 + w_0 + \beta - (w_0 - c_{\mathrm{a}}^2)a^{3(1+c_{\mathrm{a}}^2+\beta)}} - 1 - \beta, \qquad (8a)$$

$$\bar{\rho}_{\mathrm{de}} = \bar{\rho}_{\mathrm{de}}^{(0)} \frac{(1 + w_0 + \beta)a^{-3(1+c_{\mathrm{a}}^2+\beta)} - w_0 + c_{\mathrm{a}}^2}{1 + c_{\mathrm{a}}^2 + \beta}, \qquad (8b)$$

$$\begin{aligned}
\bar{\rho}_{\mathrm{c}} = \bar{\rho}_{\mathrm{c}}^{(0)} a^{-3} + \beta \bar{\rho}_{\mathrm{de}}^{(0)} \Bigg[ \left( \frac{A}{c_{\mathrm{a}}^2 + \beta} + B \right) a^{-3} \\
- \frac{A}{c_{\mathrm{a}}^2 + \beta} a^{-3(1+c_{\mathrm{a}}^2+\beta)} - B \Bigg], \qquad (8c)
\end{aligned}$$

$$A = \frac{1 + w_0 + \beta}{1 + c_{\mathrm{a}}^2 + \beta}, \quad B = \frac{w_0 - c_{\mathrm{a}}^2}{1 + c_{\mathrm{a}}^2 + \beta},$$

where $w_0$, $\bar{\rho}_{\mathrm{de}}^{(0)}$, $\bar{\rho}_{dm}^{(0)}$ are the values of EoS parameter, DE density and DM density at present time ($a = 1$).

Also the extension of interaction term (5) to the background plus perturbation case is made as follows $J_i = 3\beta H \rho_{\mathrm{de}} u_i^{(\mathrm{c})}$ in works [24, 25]. This interaction form is not general-covariant. So in this work, the interaction term is taken in following form:

$$J_i = 3\beta \rho_{\mathrm{de}} u^{(T)k}_{;k} u_i^{(\mathrm{c})}, \qquad (9)$$

where $u_k^{(T)}$ is the 4-velocity of the center of mass of all components in the universe. The presence of scalar quantity $u^{(T)k}_{;k}$ in this interaction term means that it takes into account the local deviations of the Hubble parameter from its background value $H$, which was first proposed in work [30]. Another general covariant form of $J_i$, which takes into account the perturbations of $H$, but is not considered in this work, was proposed in [31].

The resulting equations for the cosmological perturbations of interacting dark components, following from (4), in Fourier space, in synchronous gauge and in the dark matter rest frame, take the following form [23]:

$$\dot{\delta}_{\rm de} = -3aH(c_{\rm s}^2 - w)\delta_{\rm de} - (1+w)\frac{\dot{h}}{2} - (1+w)[k^2 + 9a^2H^2(c_{\rm s}^2 - c_{\rm a}^2)]\frac{\theta_{\rm de}}{k^2}$$
$$- \beta\left[\frac{\dot{h}}{2} + \theta_T + 9a^2H^2(c_{\rm s}^2 - c_{\rm a}^2)\frac{\theta_{\rm de}}{k^2}\right], \quad (10a)$$

$$\dot{\theta}_{\rm de} = -aH(1-3c_{\rm s}^2)\theta_{\rm de} + \frac{c_{\rm s}^2k^2}{1+w}\delta_{\rm de} + 3aH\frac{\beta}{1+w}(1+c_{\rm s}^2)\theta_{\rm de}\,, \quad (10b)$$

$$\dot{\delta}_{\rm c} = -\frac{\dot{h}}{2} - \beta\frac{\bar{\rho}_{\rm de}}{\bar{\rho}_{\rm c}}\left[3aH(\delta_{\rm c} - \delta_{\rm de}) - \frac{\dot{h}}{2} - \theta_T\right], \quad (10c)$$

where $c_{\rm s}^2$ is a comoving effective sound speed of DE, $\theta \equiv i(\mathbf{k}, \mathbf{v})$ and

$$\theta_T = \frac{\sum_N(\bar{\rho}_N + \bar{p}_N)\theta_N}{\sum_N(\bar{\rho}_N + \bar{p}_N)}\,,$$

where $N$ denotes the number of each component in the universe.

In this work, the quintessence model of dynamical IDE is considered. So for the quintessence DE of our model, with the small values of scale factor $a \ll 1$, the EoS parameter is equal to the square of adiabatic sound speed $w_0 = c_{\rm a}^2$. Using this property of the EoS parameter evolution, the solutions of perturbation equations (10) can be obtained at radiation-domination epoch and in the supper-horizon scales ($k\eta \ll 1$):

$$\delta_{\rm de}^{\rm init} = \frac{3}{2}\frac{C}{E}\delta_g^{\rm init}\,, \quad (11a)$$

$$\theta_{\rm de}^{\rm init} = 18\frac{D}{E}\theta_g^{\rm init}\,, \quad (11b)$$

$$\delta_{\rm c}^{\rm init} = \frac{3}{4}\delta_g^{\rm init}\,, \quad (11c)$$

$$C = (1 + c_{\rm a}^2 + \beta)[(4 - 3c_{\rm s}^2)(1 + c_{\rm a}^2) - 3\beta(1 + c_{\rm s}^2)]\,,$$
$$D = c_{\rm s}^2(1 + c_{\rm a}^2 + \beta),$$
$$E = 2(1 + c_{\rm a}^2)(4 + 3c_{\rm s}^2 - 6c_{\rm a}^2) - 3\beta(2 + 5c_{\rm s}^2 - 3c_{\rm a}^2)\,,$$

where $\delta_g^{\rm init}$, $\theta_g^{\rm init}$ are initial perturbations of the electromagnetic radiation component. These solutions had been used as initial conditions when the integration of the system of perturbation equations was made.

## III. OBSERVATIONAL DATA AND METHOD

To obtain the observational constraints on the parameters of our model, the following cosmological and astrophysical data were used:

**1. CMB temperature and polarization anisotropies.** The cosmological data on the anisotropies of the CMB were obtained by Planck Collaboration (Planck 2018 data release) [32]. They contain the information on high-$l$ TT, TE, EE power spectra and low-$l$ TT and EE power spectra. Also in addition to this, the data on the CMB weak gravitational lensing (Planck 2018 lensing) [33] were used.

**2. BAO data.** The following BAO observational data were used: SDSS-III Baryon Oscillation Spectroscopic Survey, DR12 [34]; the 6dF Galaxy Survey [35]; SDSS DR7 Main Galaxy Sample [36].

**3. SN Ia data.** Pantheon dataset [37], which contains data on 1048 supernova of type Ia.

| Parameter | Prior |
|---|---|
| $\Omega_b h^2$ | [0.005, 0.1] |
| $\Omega_c h^2$ | [0.001, 0.99] |
| $100\,\theta_{\rm MC}$ | [0.5, 10] |
| $\tau$ | [0.01, 0.8] |
| $\log(10^{10}A_{\rm s})$ | [1.61, 3.91] |
| $n_{\rm s}$ | [0.8, 1.2] |
| $\tilde{w}_0$ | [−1, −0.333] |
| $\tilde{c}_{\rm a}^2$ | [−1, 0] |
| $\beta$ | [−0.3, 0] |

Table 1. Priors for independent parameters

For constraining the dynamical IDE model parameters, the Markov Chain Monte-Carlo (MCMC) statistical method was used. For this, the CosmoMC software package [38] was modified for our model. For the calculation of observable quantities of the model, the CAMB code [39] was used, also modified for this purpose. The space of independent parameters has three parameters $w_0$, $c_{\rm a}^2$, $\beta$, in addition to the standard parameters of $\Lambda$CDM model. As the DE quintessence-phantom divide is shifted by $\beta$ [22], for the quintessence model the following conditions must be satisfied $w_0, c_{\rm a}^2 > -1 - \beta$. So it is convenient to introduce the renormalized quantities $\tilde{w}_0 = w_0 + \beta$ and $\tilde{c}_{\rm a}^2 = c_{\rm a}^2 + \beta$. Now for DE to be the quintessential, the renormalized quantities must satisfy these conditions: $\tilde{w}_0, \tilde{c}_{\rm a}^2 > -1$. For the interaction parameter $\beta$, the negative values are taken in the parameter priors, because at these values the DE cosmological perturbations are stable [23]. Also the negative values of $\beta$ are preferred by MCMC constraints of quintessence IDE, made in the works [15, 40]. The resulting table of independent parameter priors taken in our MCMC model constraints are given in Table 1.

In the MCMC simulation, the 8 chains were used. The Gelman–Rubin parameter, used as the measure of the chain convergence, is taken $R-1<0.01$ for the MCMC chains being converged.

| Parameter | 68% limits |
|---|---|
| $\boldsymbol{\Omega_b h^2}$ | $0.02243 \pm 0.00014$ |
| $\boldsymbol{\Omega_c h^2}$ | $< 0.0767$ |
| $\boldsymbol{\tau}$ | $0.0583^{+0.0068}_{-0.0078}$ |
| $\boldsymbol{\tilde{w}_0}$ | $< -0.988$ |
| $\boldsymbol{\tilde{c}_a^2}$ | $< -0.586$ |
| $\boldsymbol{\beta}$ | $-0.157^{+0.048}_{-0.11}$ |
| $\boldsymbol{\ln(10^{10} A_s)}$ | $3.051^{+0.014}_{-0.015}$ |
| $\boldsymbol{n_s}$ | $0.9668 \pm 0.0038$ |
| $H_0$ | $67.36^{+0.52}_{-0.45}$ |
| $\Omega_{de}$ | $0.823^{+0.11}_{-0.052}$ |
| $\Omega_m$ | $0.177^{+0.052}_{-0.11}$ |
| $\sigma_8$ | $1.78^{+0.19}_{-0.98}$ |
| $S_8$ | $1.18^{+0.11}_{-0.36}$ |
| $w_0$ | $-0.833^{+0.11}_{-0.050}$ |
| $c_a^2$ | $-0.52^{+0.16}_{-0.32}$ |

Table 2. The parameter constraints of the dynamical IDE model given at 68% CL

## IV. RESULTS

The results on the MCMC constraining of the dynamical IDE model parameters are given in Table 2 for 68% CL limit. The comparison of the model with observational data prefers a non-zero value of interaction parameter $\beta$ at $2.05\sigma$ significance level. Also there is degeneracy between $\Omega_c h^2$ and $\beta$ parameters as it is seen from the 2D-marginalized distribution of $\Omega_c h^2$–$\beta$ parameters shown in Fig. 1. This occurs because the amount of DM in the universe is directly dependent on the energy transfer rate from DM to DE. This fact does not allow us to determine the $\Omega_c h^2$ lower bound in the considered model using Planck 2018+lensing, BAO and Pantheon datasets only. In work [40] for a $\xi q$CDM model (with the interaction of form $J_i = \xi H \rho_{\rm de} u_i^{(c)}$) such degeneracy also occurred, with the absence of a lower bound constraint on $\Omega_c h^2$. For the same interaction in the quintessence IDE model (but with the priors of $\xi$ bounded to the positive values), considered in work [41], and the vacuum IDE model considered in work [31] (Model IV) and in work [40] (model $\xi\Lambda$CDM), the degeneracy between these parameters is also present when constraining model parameters using the Planck data only, and breaks down when adding additional datasets. So it is expected that adding other observational data which were not used in the MCMC parameter constraints in our work would break this $\Omega_c h^2$–$\beta$ degeneracy and give the tighter bounds on the dynamical IDE model parameters. This behaviour of the IDE model can also be different for the other forms of interaction $J_i$, such as for Model II and Model III in [31], where the correlation between $\Omega_c h^2$ and $\beta$ is much smaller. The negative non-zero value of $\beta$ means that in future epochs of the universe the energy transfer from DM to DE will lead to negative values of the DM energy density $\rho_c$.

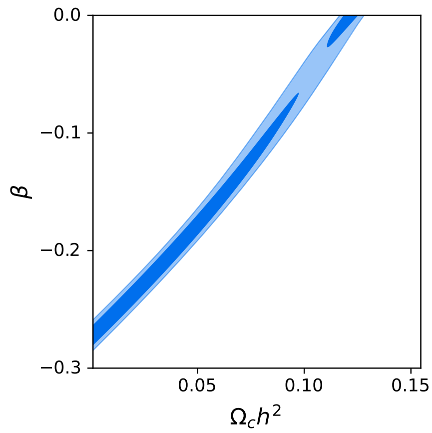


Fig. 1. The 2D marginalized distribution in $\Omega_c h^2$–$\beta$ plane of the dynamical IDE model

Also, the upper bound of the DE EoS parameter at present time $w_0$ overlaps with the lower bound of the square of the DE adiabatic sound speed $c_{\rm a}^2$, as it is shown in Table II. Hence we cannot determine with high significance level whether $w$ in our model varies with the expansion of the universe.

## V. CONCLUSIONS

In this work, a constraints on the model parameters of dynamical interacting quintessence dark energy were obtained. Unlike the previous works on this kind of cosmological models, constraints were obtained for the first time for the model in which the coupling in dark sector has the general-covariant form and the evolution of the dark energy equation of state parameter is dependent on the internal properties of dark energy including its coupling with dark matter. From the results of the parameter constraining using CMB, BAO and SN Ia observational data follows the non-zero value of the coupling parameter at $2.05\sigma$ significance level. However, the constraints on the evolution of the dark energy equation of state parameter are not very tight, so it is uncertain whether the dark energy is dynamical at all. Also there is degeneracy between the amount of the dark matter in the universe and the interaction strength in the dark sector, which does not allow us to obtain the lower bound on the $\Omega_c h^2$ parameter. It is expected that using additional observational data in the future statistical analysis of this model will give more precise constraints on its parameters.

## VI. ACKNOWLEDGEMENTS

This work was supported by the project of the Ministry of Education and Science of Ukraine "Modeling the luminosity of elements of the large-scale structure of the early universe and the remnants of galactic supernovae, the observation of variable stars" (state registration number 0122U001834) and by the National Research Foundation of Ukraine under Project No. 2020.02/0073.

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## ОБМЕЖЕННЯ НА ВЗАЄМОДІЮ КВІНТЕСЕНЦІЙНОЇ ТЕМНОЇ ЕНЕРҐІЇ З ТЕМНОЮ МАТЕРІЄЮ ТА ЕВОЛЮЦІЮ ЇЇ ПАРАМЕТРА РІВНЯННЯ СТАНУ

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Розглянуто космологічну модель із неґравітаційною взаємодією між динамічною квінтесенційною темною енерґією і темною матерією. Було вперше отримано обмеження на параметри цієї моделі, у якій еволюція параметра рівняння стану темної енерґії залежить від її внутрішніх властивостей і від сили взаємодії прихованих компонент. Така модель еволюції є більш фізично реалістичною, на відміну від раніше запропонованих. Для обмеження на значення параметрів використовували статистичний метод Марковських ланцюжків Монте–Карло. Цю модель зіставляли зі спостережуваними даними з анізотропії реліктового випромінювання, баріонних акустичних осциляцій та наднових типу Ia. З отриманих обмежень випливає наявність перетікання енерґії від темної матерії до квінтесенційної темної енерґії на рівні достовірності $2.05\sigma$. Водночас не вдалося знайти нижню межу параметра $\Omega_c h^2$ внаслідок існування виродженості під час обмеження параметрів між кількістю темної матерії у всесвіті й параметром взаємодії між прихованими компонентами, що є характерним для цього класу космологічних моделей. З попередніх робіт по взаємодіючій темній енергії випливає, що цю виродженість можна усунути, розглянувши додаткові спостережувані дані. Так само використані в цій роботі дані не дають змоги встановити наявність еволюції параметра рівняння стану квінтесенційної темної енерґії.

**Ключові слова:** взаємодіюча темна енергія, темна матерія, космологічні збурення.