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Observational constraints on the dark energy and dark matter mutual coupling

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ABSTRACT

We examine different phenomenological interaction models for Dark Energy and Dark Matter by performing statistical joint analysis with observational data arising from the 182 Gold type Ia supernova samples, the shift parameter of the Cosmic Microwave Background given by the three-year Wilkinson Microwave Anisotropy Probe observations, the baryon acoustic oscillation measurement from the Sloan Digital Sky Survey and age estimates of 35 galaxies. Including the time-dependent observable, we add sensitivity of measurement and give complementary results for the fitting. The compatibility among three different data sets seem to imply that the coupling between dark energy and dark matter is a small positive value, which satisfies the requirement to solve the coincidence problem and the second law of thermodynamics, being compatible with previous estimates.

Our universe is undoubtedly undergoing an accelerated expansion driven by a yet unknown dark energy (DE). The leading interpretation of such a DE is a cosmological constant. Although this interpretation is consistent with observational data, it entails unsurmountable problems on the theoretical side. The observational allowed value of the cosmological constant falls far below the value predicted by any sensible quantum field theory and it unavoidably leads to the coincidence problem, i.e., "why are the vacuum and matter energy densities of precisely the same order today?". Other interpretations of the DE, including quintessence and phantom fields have been proposed (for a review see [1]). But there is no clear winner in sight until now to explain the DE and solve the coincidence problem.

Since DE occupies almost 70% of the energy content of the universe today, it is natural to consider its interaction with the remaining fields of Standard model and its generalizations. It has been claimed that the coupling between DE and dark matter (DM) can provide a mechanism to alleviate the coincidence problem [2,3]. Furthermore, it has been argued that an appropriate interaction between DE and DM can influence the perturbation dynamics and affect the lowest multipoles of the CMB spectrum [4,5]. Recently, it has been shown that such an interaction could be inferred from the expansion history of the universe, as manifested in the supernova data together with CMB and large-scale structure [6]. However, the observational limits on the strength of such an interaction remain weak [7]. Signature of the interaction between DE and DM in the dynamics of galaxy clusters has also been analyzed [8,9]. Other discussions on the interaction between dark sectors can be found in [10–12].

The interaction between DE and DM is a major issue to be confronted in studying the physics of DE. However, since neither DE nor DM is actually known to us, it is hard to describe the interaction from first principles. Some attempts to discriminate the interaction from the thermodynamical point of view have been raised recently [13,14]. Most studies on the interaction between dark sectors rely either on the assumption of interacting fields from the outset [15,16], or from phenomenological requirements [4,7,10,17]. In view of continuity equations, the interaction between DE and DM must be a function of the energy density multiplied by a quantity with units of inverse of time, which can be chosen as the Hubble factor H. There is freedom to choose the form of the energy density, which can be any combination of DE and DM. Thus, the interaction between DE and DM could be expressed phenomenologically in forms such as $Q = Q(H\rho_{\rm DM})$ [7,17], $Q = Q(H\rho_{\rm DE})$ [14], $Q = Q(H(\rho_{\rm DE} + \rho_{\rm DM}))$ [4,10].

It is of great interest to investigate effects of different forms of interaction between DE and DM on the universe evolution. In [17] the impact of the interaction proportional to the DM energy density on the determination of a redshift dependent DE equation of state (EOS) and on the DM density today has been studied from SNIa data. It has been shown that the presence of such a coupling increases the tension between the CMB data from the analysis of the shift parameter and SNIa data for realistic values of the present DM density fraction. Recently, a statistical joint analysis by using observational data coming from the new 182 Gold type Ia supernova samples, the shift parameter of the Cosmic Mi-

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crowave Background given by the three-year Wilkinson Microwave Anisotropy Probe observations and the baryonic acoustic oscillation measurement from the Sloan Digital Sky Survey has been carried out for the interaction between DE and DM [18]. Comparisons concerning the influence on cosmological parameters and the effect on solving cosmic coincidence problem among different forms of phenomenological interaction models have been done. It was argued that consequences of DE and DM interaction on cosmological parameters are sensitive to the DE EOS. Choosing an appropriate EOS and the interaction in proportional to the energy density of DE, a positive coupling turns out to be more probable and the coincidence problem gets alleviated. However, for other forms of the phenomenological interaction models and for other DE EOS, one gets a negative coupling between dark sectors which will result in unphysical situations and fail to solve the coincidence prob-

Table 1
Parameters at 68.3% confidence level

Coupling	EoS	w_0	w_1	Ω_m	δ
T	$\omega_{\rm I}$	$-1.10^{+0.15}_{-0.15}$	$1.22^{+0.20}_{-0.27}$	$0.27^{+0.02}_{-0.02}$	$-0.01^{+0.07}_{-0.04}$
T	$\omega_{\rm II}$	$-1.50^{+0.31}_{-0.30}$	$3.90^{+2.09}_{-2.31}$	$0.26^{+0.02}_{-0.02}$	$0.01^{+0.03}_{-0.03}$
DM	$\omega_{\rm I}$	$-1.17^{+0.16}_{-0.14}$	$1.28^{+0.21}_{-0.32}$	$0.27^{+0.02}_{-0.02}$	$-0.02^{+0.31}_{-0.06}$
DM	$\omega_{\rm II}$	$-1.50^{+0.32}_{-0.31}$	$3.91^{+2.12}_{-2.34}$	$0.25^{+0.02}_{-0.02}$	$0.01^{+0.04}_{-0.04}$
DE	$\omega_{\rm I}$	$-1.11^{+0.17}_{-0.16}$	$1.19^{+0.19}_{-0.28}$	$0.27^{+0.01}_{-0.01}$	$-0.04^{+0.13}_{-0.13}$
DE	$\omega_{\rm II}$	$-1.49^{+0.31}_{-0.30}$	$3.78^{+2.13}_{-2.39}$	$0.26^{+0.02}_{-0.02}$	$0.05^{+0.06}_{-0.10}$

Note—(1) The flat priors on the parameters for EoS1 are, $-10 < w_0 < 10$, $-10 < w_1 < 10$, $0 < \Omega_m < 0.8$, $-0.5 < \delta < 0.5$; (2) For EoS2, $-10 < w_0 < 10$, $-15 < w_1 < 15$, $0 < \Omega_m < 0.8$, $-1 < \delta < 1$. The CMBEASY GUI is utilized to process the MCMC chains.

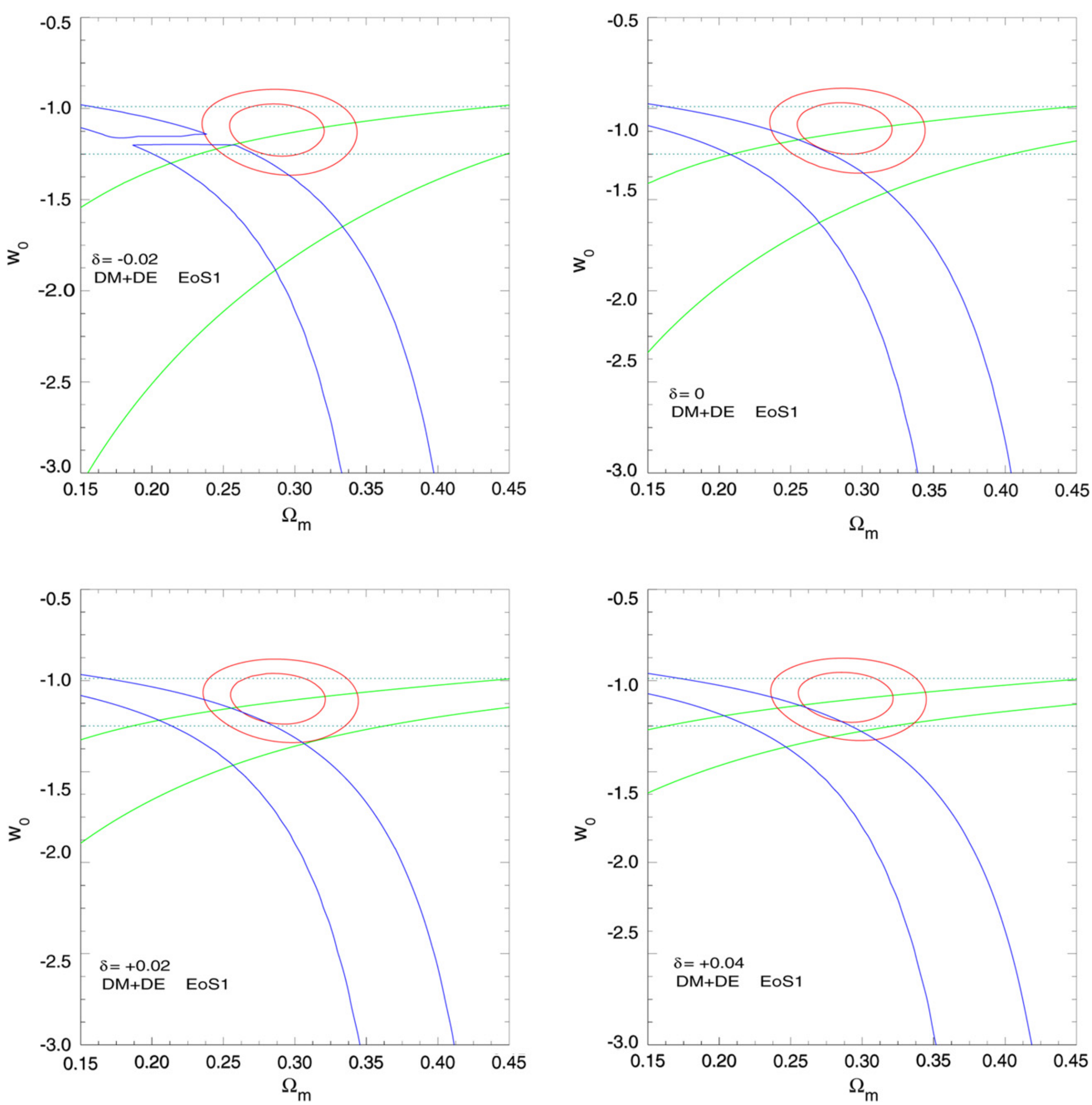

Fig. 1. Contour plots in the Ω_m–w_0 plane for a variable EoS $\omega_{\rm I}$ when Q is proportional to the total energy density of DM and DE after giving a prior to $w_1 = 1.22$. The compatibility among CMB, SNIa + BAO, Lookback time can be compared by examining the 2σ contour of CMB shift constraint (green line), the Lookback time constraint (blue line), and 1σ, 2σ contours of SNIa + BAO result (red line). The 5 years WMAP results for w_0 are also indicated by parallel lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

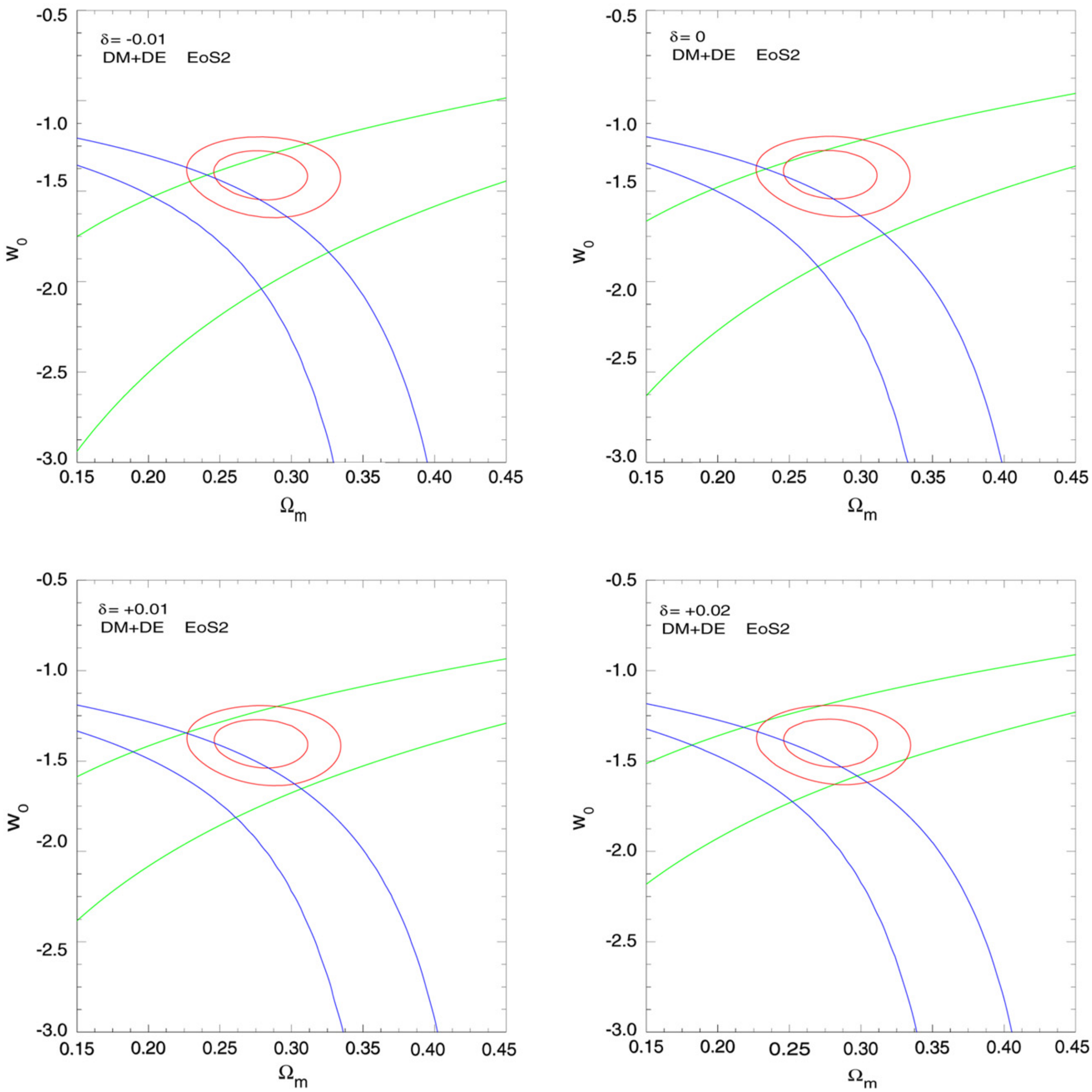

Fig. 2. Contour plots in the Ω_m–w_0 plane for a variable EoS ω_{II} when Q is proportional to the total energy density of DM and DE after giving a prior to $w_1 = 3.90$. Green lines are for 2σ contours of CMB shift constraint, blue lines are for the Lookback time constraints and red lines are for 1σ, 2σ contours of SNIa + BAO results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

lem. The negative coupling has also been seen by using the same data from SNIa together with CMB and large-scale structure for the interacting holographic DE model with the interaction proportional to the total dark sector energy density [6] and other models describing the interaction in proportional to the DM energy density [7]. It was argued that the negative coupling is not able to alleviate the coincidence problem [19] and the model does not obey the second law of thermodynamics [14]. Using the galaxy cluster data, the coupling was obtained to be positive indicating the energy decay from DE to DM.

To reduce the uncertainty and put tighter constraint on the value of the coupling between DE and DM, new observables should be added. Recalling that the test of cosmological models by SNIa data is a distance based method, it is of interest to look for tests based on time-dependent observables. In [5,20], the age of an old high redshift galaxy has been used to constrain the model. To overcome the problem that the estimate of the age of a single galaxy may be affected by systematic errors, it is needed to consider a sample of galaxies belonging to the same cluster. In this work we will combine four fundamental observables including the new 182 Gold SNIa samples, the shift parameter of the CMB given by the three-year Wilkinson Microwave Anisotropy Probe observations, the baryon acoustic oscillation (BAO) measurement from the Sloan Digital Sky Survey and age estimates of 35 galaxies provided in [27] to perform the joint systematic analysis of the coupling between dark sectors. We expect that sensitivities of measurements of different observables can give complementary results on the coupling between dark sectors. We will compare the compatibility among SNIa data including BAO, CMB and age data and determine the tendency of the coupling results.

Concerning energy conservation, we can suppose that the interaction between DE and DM is described by

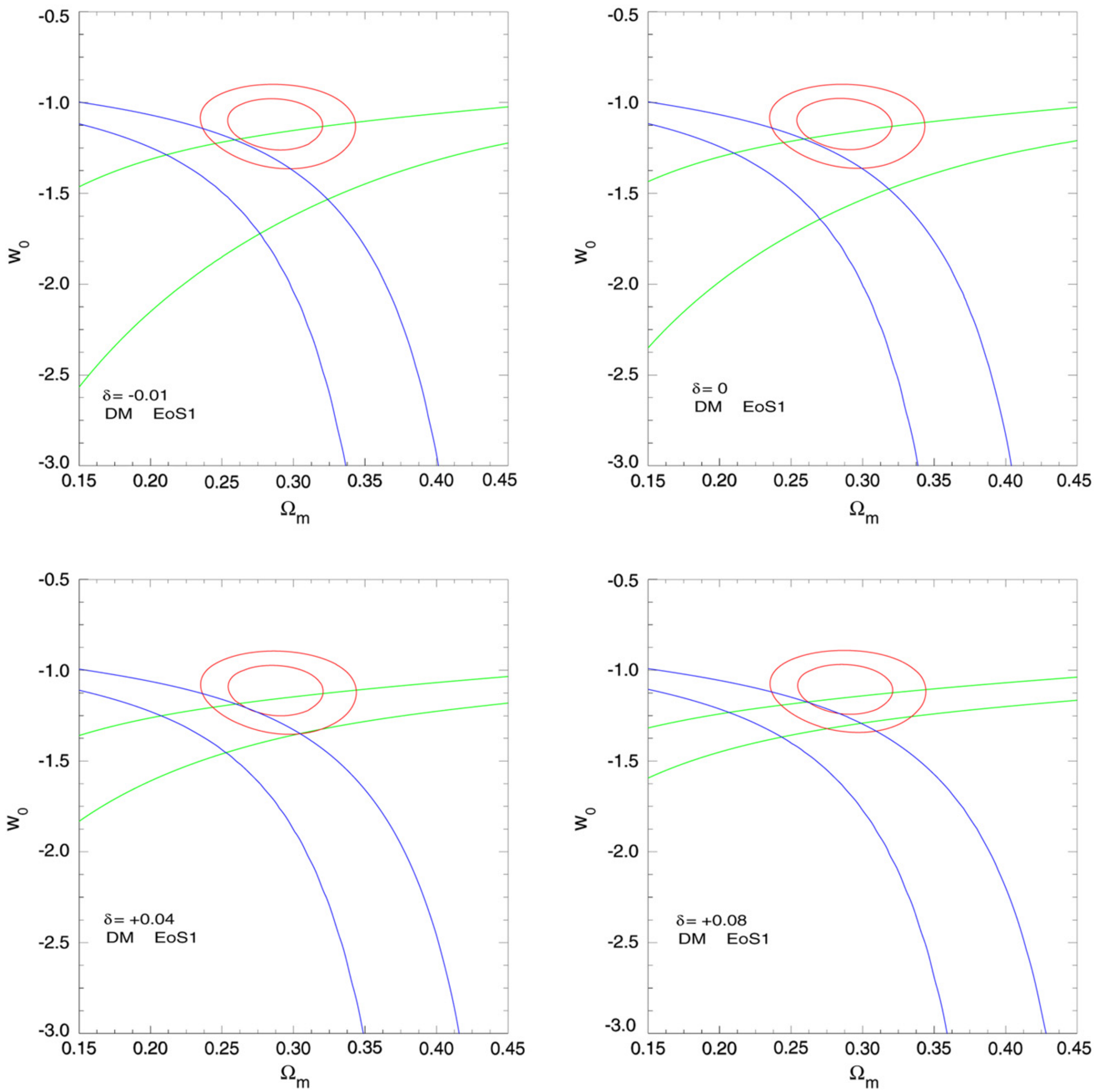

Fig. 3. Contour plots in the Ω_m–w_0 plane for a variable EoS ω_{I} when Q is proportional the energy density of DM after giving a prior to $w_1 = 1.28$. Green lines are for 2σ contours of CMB shift constraint, blue lines are for the Lookback time constraints and red lines are for 1σ, 2σ contours of SNIa + BAO results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

$$\dot{\rho_m} + 3H\rho_m = Q, \tag{1}$$

$$\dot{\rho_D} + 3H(1+\omega_D)\rho_D = -Q, \tag{2}$$

where Q denotes the interaction term. Notice that the overall energy density of dark sectors $\rho_{\mathrm{DE}} + \rho_{\mathrm{DM}}$ is conserved.

From the equations above, phenomenological forms of the interaction between DE and DM must be a function of the energy densities multiplied by a quantity with units of inverse of time, which have possible expressions, such as (1) $Q = \delta H(\rho_{\mathrm{DM}} + \rho_{\mathrm{DE}})$, (2) $Q = \delta H \rho_{\mathrm{DM}}$ and (3) $Q = \delta H \rho_{\mathrm{DE}}$, etc.

We will constrain the coupling between DE and DM in different phenomenological interaction models by using the latest observations (golden SN Ia, the shift parameter of CMB and the BAO) combining them with the lookback time data. We will not specify any special model of DE. Considering recent accurate data analysis showing that the time varying DE gives a better fit than a cosmological constant and in particular, DE EoS can cross −1 around $z = 0.2$ from above to below [21], we will employ two commonly used parameterizations in our work, namely

$$\omega_{\mathrm{I}}(z) = w_0 + \frac{w_1 z}{(1+z)}, \tag{3}$$

$$\omega_{\mathrm{II}}(z) = w_0 + \frac{w_1 z}{(1+z)^2}. \tag{4}$$

The up-to-date gold SN Ia sample was compiled by Riess et al. [22]. This sample consists of 182 data, in which 16 points with $0.46 < z < 1.39$ were obtained recently by the Hubble Space Telescope (HST), 47 points with $0.25 < z < 0.96$ by the first year Supernova Legacy Survey (SNLS) and the remaining 119 points are old data. The SN Ia observation gives the distance modulus of a SN at the redshift z. The distance modulus is defined as

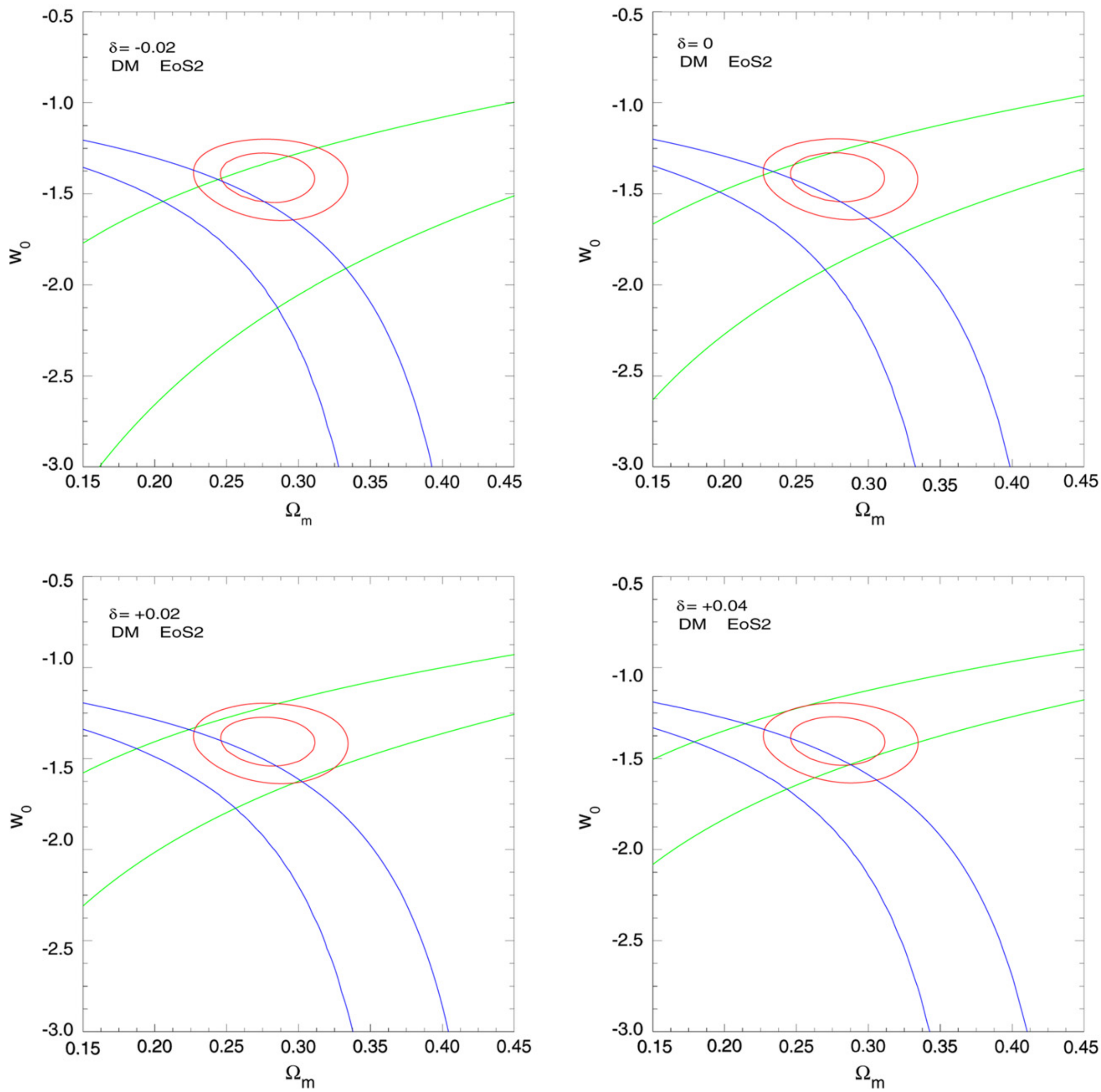

Fig. 4. Contour plots in the Ω_m–w_0 plane for a variable EoS $\omega_{\rm II}$ when Q is proportional to the DM energy density after giving a prior to $w_1 = 3.91$. Green lines are for 2σ contours of CMB shift constraint, blue lines are for the Lookback time constraints and red lines are for 1σ, 2σ contours of SNIa + BAO results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

$$\mu_{th}(z;\mathbf{P},\tilde{M}) = 5\log_{10}\big(d_L(z)/\mathrm{Mpc}\big) + 25$$
$$= 5\log_{10}\left[(1+z)\int_0^z \frac{dz'}{E(z')}\right] + 25 - 5\log_{10} H_0, \qquad (5)$$

where the luminosity distance $d_L(z) = \frac{(1+z)}{H_0}\int_0^z \frac{dz'}{E(z')}$, the nuisance parameter $\tilde{M} = 5\log_{10} H_0$ is marginalized over by assuming a flat prior $P(H_0) = 1$ on H_0 and $\mathbf{P}$ describes a set of parameters characterizing the given model.

An efficient way to reduce the degeneracies of the cosmological parameters is to use the SN Ia data in combination with the BAO measurement from SDSS [23] and the CMB shift parameter [24]. The acoustic signatures in the large scale clustering of galaxies yield additional test for cosmology. Using a large sample of 46748 luminous red galaxies covering 3816 square degrees out to a redshift of $z = 0.47$ from the SDSS, Eisenstein et al. [23] have found the model independent BAO measurement which is described by the A parameter

$$A = \sqrt{\Omega_m}\,E(z_{\rm BAO})^{-1/3}\left[\frac{1}{z_{\rm BAO}}\int_0^{z_{\rm BAO}} \frac{dz'}{E(z')}\right]^{2/3}$$
$$= 0.469\left(\frac{n_s}{0.98}\right)^{-0.35} \pm 0.017, \qquad (6)$$

where n_s can be taken as 0.95 [25] and $z_{\rm BAO} = 0.35$.

The CMB shift parameter is given by

$$R = \sqrt{\Omega_m}\int_0^{z_{ls}} \frac{dz'}{E(z')}, \qquad (7)$$

where $z_{ls} = 1089$. This CMB shift parameter R captures how the l-space positions of the acoustic peaks in the angular power spec-

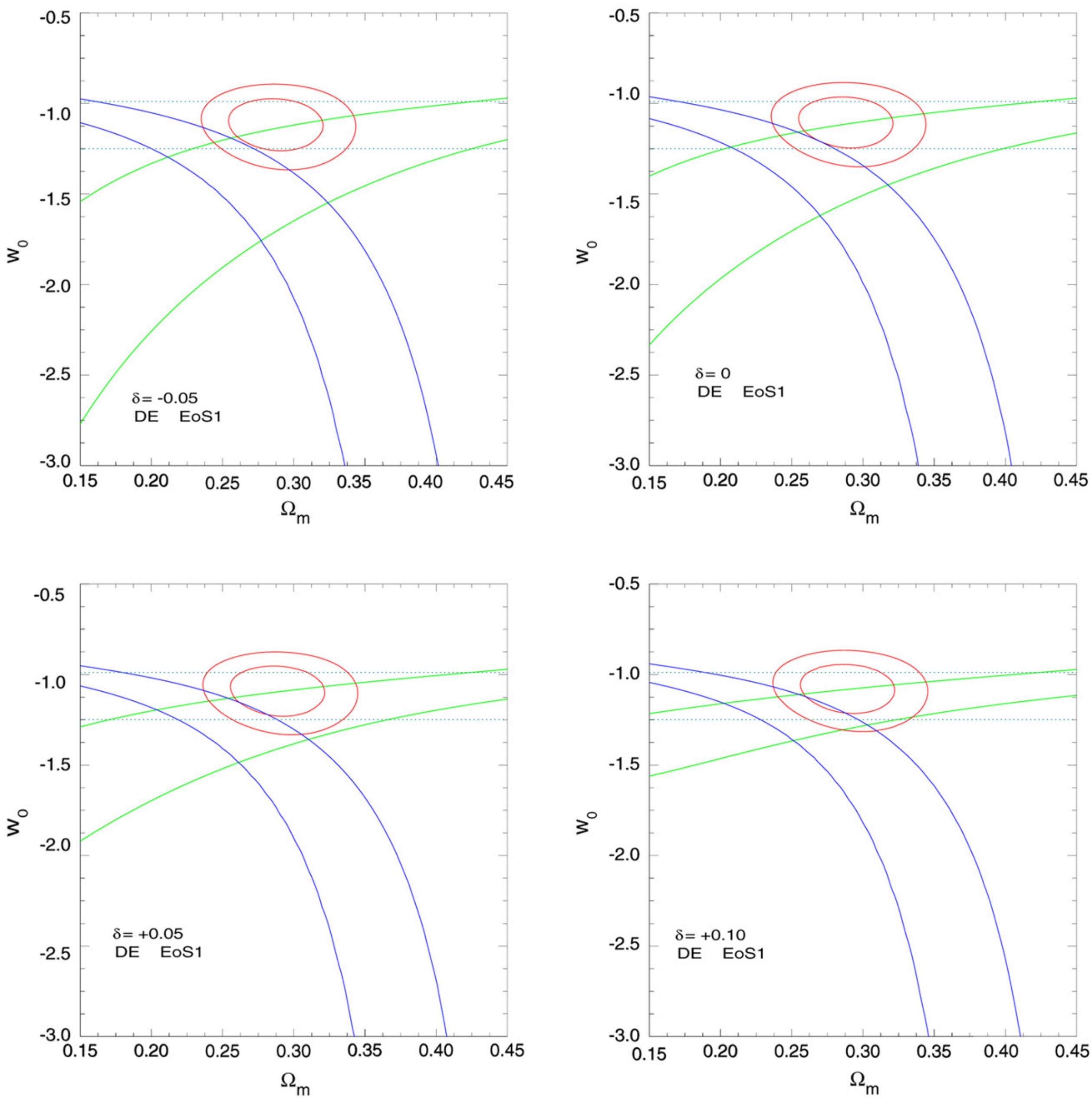

Fig. 5. Contour plots in the Ω_m–w_0 plane for a variable EoS ω_l when Q is in proportional to the DE energy density after giving a prior to $w_1 = 1.19$. Green lines are for 2σ contours of CMB shift constraint, blue lines are for the Lookback time constraints and red lines are for 1σ, 2σ contours of SNIa + BAO results. The 5 years WMAP results for w_0 are also indicated by parallel lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

trum shift. Its value is expected to be the least model independent and can be extracted from the CMB data. The WMAP3 data [25] gives $R = 1.70 \pm 0.03$ [24].

We now turn to the lookback time observations. They have been used in [26] and have been shown effective to provide a complementary test of different models. By assuming the total age of the universe to be $t_0 = 13.7 \pm 0.2$ Gyr, as given by current CMB measurement [25], we transform the age estimates of 35 galaxies provided in [27]. The lookback time-redshift relation is defined by

$$t_L(z; \mathbf{P}) = H_0^{-1} \int_0^z \frac{dz'}{(1+z')E(z')}, \tag{8}$$

where $H_0^{-1} = 9.78h^{-1}$ Gyr. We have adopted the recent value 0.72 for h given by the HST key project [28], $\mathbf{P}$ stands for the model parameters. To use the lookback time and the age of the universe to test a given cosmological model, we follow [29] and consider an object i whose age $t_i(z)$ at redshift z is the difference between the age of the universe when it was born at redshift z_F and the universe age at z,

$$t_i(z) = H_0^{-1}\left[\int_{z_i}^{\infty} \frac{dz'}{(1+z')E(z')} - \int_{z_F}^{\infty} \frac{dz'}{(1+z')E(z')}\right]. \tag{9}$$

Using the lookback time definition, we have $t(z_i) = t_L(z_F) - t_L(z)$. Thus the lookback time to an object at z_i can be expressed as

$$\begin{aligned} t_L^{\text{obs}}(z_i) &= t_L(z_F) - t(z_i) = \left[t_o^{\text{obs}} - t_i(z)\right] - \left[t_o^{\text{obs}} - t_L(z_F)\right] \\ &= t_o^{\text{obs}} - t_i(z) - df, \end{aligned} \tag{10}$$

where $df = t_o^{\text{obs}} - t_L(z_F)$ is the delay factor.

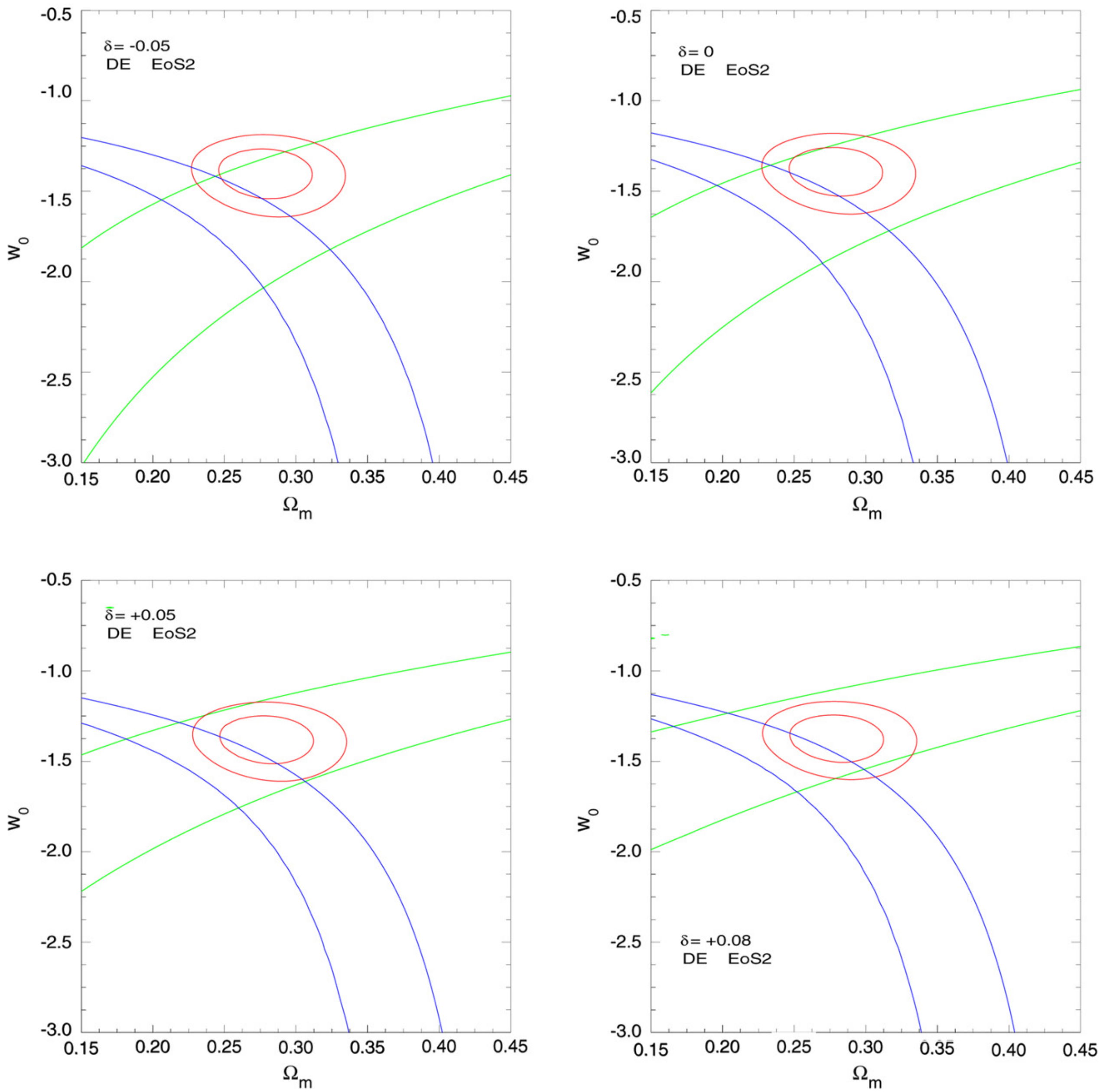

Fig. 6. Contour plots in the Ω_m–w_0 plane for a variable EoS ω_{II} when Q is proportional to the DE energy density after giving a prior to $w_1 = 3.78$. Green lines are for 2σ contours of CMB shift constraint, blue lines are for the Lookback time constraints and red lines are for 1σ, 2σ contours of SNIa + BAO results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

We employ the Monte Carlo Markov Chain (MCMC) method [30] to explore the parameter space. By using two parameterizations for the EoS of DE ω_{I}, ω_{II}, we show in Table 1 the parameter space when the coupling between DE and DM is taken proportional to energy densities of DM, DE, total DM plus DE (T), respectively.

Comparing with the result obtained in [18], it is interesting to find that by adding the new observable, the lookback time data, it is possible to have positive coupling between DE and DM, especially for the EOS with the form ω_{II}.

We perform the data comparisons for the previously mentioned different phenomenological interaction models between DE and DM with two different parameterizations of DE EOS. By taking priority of w_1 obtained from MCMC fitting as central values, we plot the contours in Ω_{DM}–w_0 plane for different interaction models in Figs. 1, 3, 5 with DE EOS ω_{I} and Figs. 2, 4, 6 with DE EOS ω_{II}. Green lines indicate the result from CMB shift parameters and blue lines are from lookback time result.

We observe that when $|\delta|$ is over the range in Table 1, there appear poorer compatibility among the three data sets, especially between CMB and SNIa data. For the big positive δ, this incompatibility for the interaction between dark sectors proportional to the DM energy density was also observed in [17]. For small enough $|\delta|$, the range obtained from CMB shift parameters will change more compared to constraints from other two data sets. The lower green line for the CMB shift moves upper when small δ becomes more positive and the upper green line becomes more flattened. This leads more overlapped region for three data sets in the Ω_{DM}–w_0 plane for small positive value of the coupling. However when the positive coupling is over a limit, the lower green line will cut the contour, while the upper green line cannot efficiently move upper, which will reduce the overlapped region of the constraints from

Table 2
Parameters at 68.3% confidence level

Coupling	EoS	w_0	Ω_m	δ
T	$\omega_{\rm I}$	$-1.13^{+0.02}_{-0.08}$	$0.26^{+0.01}_{-0.01}$	$0.02^{+0.18}_{-0.03}$
T	$\omega_{\rm II}$	$-1.50^{+0.07}_{-0.08}$	$0.25^{+0.02}_{-0.01}$	$0.01^{+0.02}_{-0.02}$
DM	$\omega_{\rm I}$	$-1.22^{+0.04}_{-0.06}$	$0.26^{+0.01}_{-0.01}$	$0.04^{+0.16}_{-0.02}$
DM	$\omega_{\rm II}$	$-1.50^{+0.07}_{-0.08}$	$0.25^{+0.02}_{-0.02}$	$0.01^{+0.03}_{-0.03}$
DE	$\omega_{\rm I}$	$-1.18^{+0.04}_{-0.12}$	$0.26^{+0.01}_{-0.01}$	$0.06^{+0.14}_{-0.09}$
DE	$\omega_{\rm II}$	$-1.48^{+0.08}_{-0.10}$	$0.26^{+0.01}_{-0.01}$	$0.05^{+0.06}_{-0.08}$

Note—The flat priors are, $-5 < w_0 < 5$, $0 < \Omega_m < 0.5$, $-0.2 < \delta < 0.2$.

three different data sets. This result holds for all forms of phenomenological interaction models and different parameterizations of DE EOS.

Besides, in the small $|\delta|$ range, when δ becomes more positive, we observed that there are more overlaps between constraints from the SNIa + BAO and lookback time data sets. Thus from the compatibility of three different data sets we obtain the tendency of small positive coupling between DE and DM.

Choosing now the priority of w_1 as the central value from MCMC, we obtain the parameter space listed in Table 2. Using the best-fit results of these parameters, we study the coincidence problem. We pay attention to the ratio of energy densities between DE and DM, $r = \rho_{\rm DM}/\rho_{\rm DE}$, and its evolution. In Fig. 7 we show the behavior of r for the interaction between dark sectors in proportional to DM energy density when we choose DE EOS to be $\omega_{\rm II}$. For other interaction forms and for DE EOS in the form of $\omega_{\rm I}$, $\omega_{\rm II}$, r behaviors are similar. We see that with the positive coupling obtained from the best-fit leads to a slower change of r as compared to the noninteracting case. This means that the period when energy densities of DE and DM are comparable is longer compared to the noninteracting case. Thus it is not so strange that we now live in the coincidence state of the universe. In this sense the coincidence problem is less acute when compared with the case without interaction. Similar argument has also been given in [31].

It is also worthwhile commenting on the results in the light of the recent 5 years WMAP results [32]. We included, in Figs. 1 and 5 the limits for w_0 from 5 years WMAP results. They turn out to be perfectly compatible with the SNIa + BAO countours at 1σ. This implies confidence in the results of the present Letter. For positive coupling, it has more possibility for the overlapped region among three data sets to accommodate w_0 within the 5 years WMAP region, which gives further strength to the claims concerning the sign of the interaction.

In summary, we have examined different phenomenological interaction models between DE and DM by performing statistical joint analysis with observational data from the new 182 Gold type Ia supernova samples, the shift parameter of the Cosmic Microwave Background given by the three-year Wilkinson Microwave Anisotropy Probe observations, the baryon acoustic oscillation measurement from the Sloan Digital Sky Survey and age estimates of 35 galaxies. Comparing with the test by just using data from SNIa together with CMB and large-scale structure [18], we observed that adding the age constraint, we get a tendency towards a positive coupling between DE and DM, especially for the DE EOS with the form $\omega_{\rm II}$. This shows that the new observable can add sensitivity of measurement and give a complementary result for the fitting.

We have studied the compatibility among three different data sets including SNIa plus BAO, CMB shift and lookback time. We found that the bigger couplings $|\delta|$ between dark sectors lead to a poorer compatibility, especially comparing CMB with other two data sets. For small $|\delta|$, we observed, for all phenomenological forms of interaction with two parameterizations of DE EOS, the

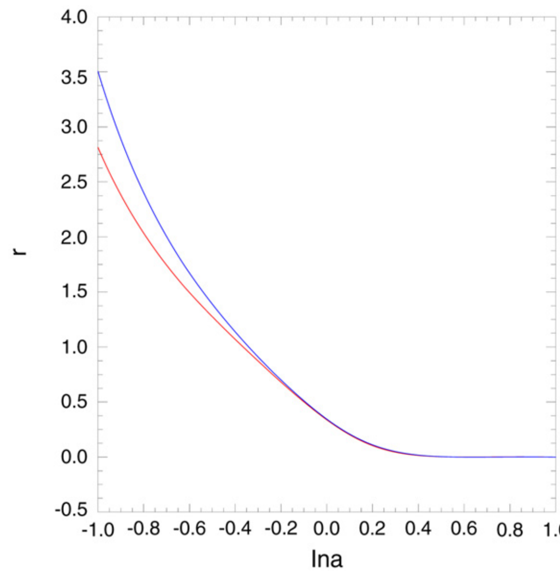

Fig. 7. The red line indicates the evolution of the ratio of energy densities between DE and DM when the interaction is in proportional to the energy density of DM and DE EoS is in the form of $\omega_{\rm II}$. We have compared the interacting case (red line) with the non-interacting case (blue line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

same tendencies for the δ to be a small positive number. The small positive coupling result is consistent with that got independently by galaxy cluster analysis [9]. The positive coupling is required to alleviate the coincidence problem and avoid some unphysical problems met in [17,18]. It is also the requirement of the second law of thermodynamics [14].

We conclude once more claiming that DM and DE interact with a coupling of the order of a few percent, in agreement with previous claims.

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