Chapter 5

Dark sector interaction: a remedy for CMB and LSS tensions

The well-known tensions on the cosmological parameters H_0 and σ_8 within the ΛCDM cosmology shown by the Planck-CMB and LSS data are possibly due to the systematics in the observational data or our ignorance of some new physics beyond the ΛCDM model. In this chapter, we ignore the possible systematics in data (if any) and focus on the second possibility. We investigate a minimal extension of the ΛCDM model by allowing coupling between its dark sector components: DE and DM, of the Universe. We investigate this coupling scenario with the data from Planck-CMB, KiDS, and HST. Here, the Planck-CMB data comprises 'Planck-highl + Planck-lowl' likelihoods, not the lensing likelihood and we refer this data simply as "Planck" throughout this chapter. The main aim of this work is to test whether there is statistical support for an interaction between DM and DE from observational data and to see whether the interaction could be a remedy of tension between Planck-CMB and LSS measurements. Here, we constrain the model parameters with Planck and KiDS data (which are in tension within the framework of ΛCDM model), separately and also jointly together with HST data. The purpose of doing this is to analyze the possible consequences of dark sector coupling, in particular on H_0

and σ_8 parameters. In addition, we constrain the standard ΛCDM model with the same set of data combinations, for comparison purposes. The research work presented in this chapter is carried out in the research paper [189].

5.1 Introduction

The CMB observations from Planck [32] together with the observations of cosmic expansion history from independent measurements, BAO [190] and SNe Ia [191], find a very good statistical fit to the standard model of cosmology, viz., the ΛCDM model. However, with the gradual increase in the data accumulation with a great precision, the latest Planck-CMB data show inconsistency with the direct measurements of Hubble expansion rate from the HST [39], and some LSS observations such as galaxy cluster counts [42,43] and weak gravitational lensing [44, 45], in the framework of the ΛCDM model. Specifically, the value of Hubble constant, H_0 and the value of root mean squared fluctuation of density perturbation estimated at the sphere of radius $8h^{-1}$ Mpc, characterized by parameter, σ_8, inferred from the CMB experiments are in a serious disagreement with the ones measured from the LSS experiments [101, 102], as discussed earlier in Chapter 1. At present, it is not clear whether these inconsistencies in the parameters are due to systematics in the data measurement or need some new physics beyond the standard ΛCDM model [46, 47]. Several studies have been carried out in the literature to reconcile these tensions between the CMB and LSS observations [49–52, 104]. But both the tensions are not resolved simultaneously at a significant statistical level. Rather, by assuming neutrino properties, the parameters are correlated in such a way that lower values of σ_8 require higher values of total matter density and smaller values of H_0, which aggravates the tensions (e.g. [53]). In [54], it is argued that the presence of sterile neutrinos (fourth kind of neutrino which is not the part of the standard model) do not bring a new concordance, but possibly indicating systematic biases in the measurements. However, recently in [55], it has been argued that incorporation of the dissipative effects in the energy momentum tensor can ameliorate both the tensions simultaneously. Likewise in [56], it is claimed that the presence of viscosity, shear or bulk or combination of both, can alleviate both the tensions simultaneously. At present, the precise nature of constituents of the dark sector in the ΛCDM model, namely CDM and DE (the vacuum energy mimicked by Λ), is unknown. Moreover, these two are major energy ingredients accounting for around 95% energy budget of the Universe. So, a possibility of an exchange of energy/momentum or interaction between the dark sector components can not be ignored, especially, when considering the current issues with the ΛCDM model. Consequently, in recent years, a large number of studies have been carried out with regard to the interaction between the dark sector components of the Universe with different motivations and perspectives [125, 141–143, 192–205] (see [206] for a review). In particular, a possible interaction in the dark sector has been investigated in [142, 143, 192, 193], where it has been argued that a dark sector coupling could be a possible remedy to the H_0 and σ_8 tensions. In light of the above discussion, it is important to investigate the possibility of interaction in the dark sector with recent cosmological observations. A strong statistical support of interaction from recent data sets might be helpful in alleviating some of the issues of the ΛCDM model.

5.2 Interacting model of dark sector

In general, the background evolution of coupled dark sector components, in the FLRW Universe, is encoded in the coupled energy-momentum conservation equations:

$$\dot{\rho}_{\rm dm} + 3H\rho_{\rm dm} = -\dot{\rho}_{\rm de} - 3H\rho_{\rm de}(1 + w_{\rm de}) = Q, \tag{5.1}$$

where an over dot stands for the cosmic time derivative; $\rho_{\rm dm}$ and $\rho_{\rm de}$ are the energy densities of DM and DE, respectively; $H = \dot{a}/a$ is the Hubble parameter with a being the scale factor of the Universe; $w_{\rm de}$ is EoS parameter of DE; and Q is the coupling function between the dark sector components, which characterizes the interaction form, viz., $Q < 0$ corresponds to energy flow from DM to DE, and $Q > 0$ the opposite case. The most commonly used forms of Q in the literature are: $Q \propto H\rho_{\rm dm}$ or $Q \propto H\rho_{\rm de}$ or their combinations [207, 208]. In this work, we use $Q \propto H\rho_{\rm de}$ in order to avoid the instability in the perturbations at early times [209, 210]. Thus, we use the form $Q = \delta H \rho_{\rm de}$, where δ is the coupling parameter that quantifies the coupling between DM and DE. With the chosen coupling function, the conservation equation where dark matter and dark energy interact reads as,

$$\begin{aligned} \dot{\rho}_{\rm dm} + 3\frac{\dot{a}}{a}\rho_{\rm dm} &= \frac{\dot{a}}{a}\delta\rho_{\rm de}, \\ \dot{\rho}_{\rm de} + 3\frac{\dot{a}}{a}(1+w_{\rm de})\rho_{\rm de} &= -\frac{\dot{a}}{a}\delta\rho_{\rm de}. \end{aligned} \tag{5.2}$$

Therefore, the evolution of density of dark energy and dark matter is given by

$$\rho_{\rm de} = \rho_{\rm de0}\, a^{-3(1+w_{\rm de})-\delta}. \tag{5.3}$$

$$\rho_{\rm dm} = \rho_{\rm dm0}\, a^{-3} + \frac{\delta\, \rho_{\rm de0}}{3w_{\rm de}+\delta} a^{-3} - \frac{\delta\, \rho_{\rm de0}}{3w_{\rm de}+\delta}\, a^{-3(1+w_{\rm de})-\delta}. \tag{5.4}$$

At perturbative level, we adopt the synchronous gauge in which the evolution of the scalar mode perturbations within a general interacting DM and DE scenario, in the Fourier space, is governed by the equations [211–213]:

$$\dot{\delta}_{\rm dm} - \frac{k^2}{a^2}\theta_{\rm dm} + \frac{\dot{h}}{2} - \frac{Q}{\rho_{\rm dm}}\delta_{\rm dm} = \frac{\dot{\delta}_{\rm de}}{\rho_{\rm dm}}, \tag{5.5}$$

$$\dot{\theta}_{\rm dm}\rho_{\rm dm} = \delta_{\rm de} + Q\theta_{\rm dm}. \tag{5.6}$$

where Q is the previously defined coupling function and h is the scalar mode in synchronous gauge. In addition, we assume the energy transfer flow between the dark sector components parallel to the four-velocity of the DM, i.e., $Q^{\mu}_{\rm dm} = -Qu^{\mu}_{\rm dm}$. Thus, there is no momentum transfer in the rest frame of DM, and the velocity perturbation for DM is not affected by the interaction, and therefore obeys the standard evolution as expected in the synchronous gauge. Therefore, the DM four-velocity $u^{\mu}_{\rm dm}$ is a geodesic flow, i.e, $u^{\mu}_{\rm dm}\nabla_{\mu}u^{\nu}_{\rm dm} = 0$. A direct consequence is that the vacuum energy perturbation contribution in the DM comoving frame is identically null. The other species (baryons, photons and neutrinos) are conserved independently, and their dynamics follow the well-known standard evolution both at the background and perturbative levels.

5.2.1 Results and discussion

Following the above arguments, in this work, we adopt $w_{\rm de} = -1$, i.e., we allow the interaction of vacuum energy with the CDM, and refer to this scenario simply as IVCDM model in the remaining text. This model is investigated in many studies eg. [192, 211, 212], and very recently in [213], but mainly in the context of interaction in the dark sector. Here, we present an analysis with the main objective to investigate whether this said dark sector interaction could be a possible remedy of the tensions between the CMB and LSS data. To analyze the IVCDM model in contrast with the ΛCDM model, we use the following observational data sets: Planck-CMB, KiDS, and HST. We analyze both the IVCDM and ΛCDM models with Planck and KiDS data separately to clearly demonstrate the issue/resolution of the tensions among the two data sets. In order to obtain more tight constraints on the model parameters, we also study two joint analyses with HST data: Planck + HST and Planck + HST + KiDS. The base parametric space for IVCDM scenario is given below:

$$\mathcal{P}_{\rm IVCDM} = \{\omega_{\rm b},\, \omega_{\rm cdm},\, A_s,\, n_s,\, h,\, \delta\}, \tag{5.7}$$

where δ is the coupling parameter and h is dimensionless reduced Hubble parameter with $H_0 = 100$h km s^{-1} Mpc^{-1}.

In all analyses performed here, we choose uniform priors on ΛCDM and IVCDM baseline parameters as shown in the second column of the Table 5.1. Table 5.1 summarizes the main results from the statistical analyses of the ΛCDM and IVCDM models with four combinations of data sets: Planck, KiDS, Planck + HST, and Planck + HST + KiDS data. We notice similar constraints on the baseline parameters $\omega_{\rm b}$, $\omega_{\rm cdm}$, A_s, n_s, in the two models in all the four cases of data sets under consideration. In what follows, we discuss the constraints on other parameters with regard to the tensions on the parameters H_0 and σ_8, in particular. First we discuss the constraints with regard to the tension on H_0. In the left panel of Figure 5.1, the $\Omega_{\rm m} - H_0$ parametric space is shown for the ΛCDM model with a yellow band corresponding to the local value $H_0 = 73.24 \pm 1.74$ km s^{-1} Mpc^{-1} [39], in

Table 5.1: Constraints at 68% CL on free and some derived parameters of the ΛCDM and IVCDM models from the four data combinations. The parameter H_0 is measured in units of km s^{-1}Mpc^{-1}. The final row displays $\chi^2_{\rm min}$ values of the statistical fit.

Parameter	Prior	Planck		KiDS		Planck + HST		Planck + HST + KiDS	
		ΛCDM	IVCDM	ΛCDM	IVCDM	ΛCDM	IVCDM	ΛCDM	IVCDM
$10^2\omega_{\rm b}$	$[1.8, 2.6]$	$2.23^{+0.02}_{-0.02}$	$2.22^{+0.02}_{-0.02}$	$2.23^{+0.20}_{-0.20}$	$2.25^{+0.20}_{-0.20}$	$2.25^{+0.02}_{-0.02}$	$2.22^{+0.02}_{-0.02}$	$2.26^{+0.20}_{-0.20}$	$2.23^{+0.02}_{-0.02}$
$\omega_{\rm cdm}$	$[0.01, 0.99]$	$0.120^{+0.002}_{-0.002}$	$0.120^{+0.002}_{-0.002}$	$0.124^{+0.040}_{-0.046}$	$0.123^{+0.042}_{-0.042}$	$0.120^{+0.002}_{-0.002}$	$0.120^{+0.002}_{-0.002}$	$0.115^{+0.001}_{-0.001}$	$0.119^{+0.002}_{-0.002}$
$\ln[10^{10}A_s]$	$[2.4, 4]$	$3.120^{+0.006}_{-0.006}$	$3.121^{+0.007}_{-0.007}$	$2.760^{+0.510}_{-1.000}$	$2.800^{+0.400}_{-1.100}$	$3.116^{+0.006}_{-0.006}$	$3.120^{+0.006}_{-0.006}$	$3.114^{+0.006}_{-0.016}$	$3.120^{+0.006}_{-0.006}$
n_s	$[0.9, 1.3]$	$0.967^{+0.005}_{-0.005}$	$0.965^{+0.005}_{-0.005}$	$1.060^{+0.220}_{-0.098}$	$1.070^{+0.210}_{-0.092}$	$0.973^{+0.005}_{-0.005}$	$0.964^{+0.006}_{-0.006}$	$0.978^{+0.005}_{-0.005}$	$0.967^{+0.006}_{-0.006}$
H_0	$[60, 90]$	$67.8^{+0.9}_{-0.9}$	$72.2^{+3.5}_{-5.0}$	$73.6^{+7.8}_{-3.6}$	$74.2^{+7.5}_{-5.1}$	$68.9^{+0.8}_{-0.8}$	$72.9^{+1.7}_{-1.7}$	$69.7^{+0.7}_{-0.7}$	$73.6^{+1.6}_{-1.6}$
δ	$[-1, 1]$	0	$-0.34^{+0.40}_{-0.26}$	0	$-0.23^{+0.43}_{-0.43}$	0	$-0.40^{+0.17}_{-0.14}$	0	$-0.40^{+0.16}_{-0.14}$
$\Omega_{\rm m}$	–	$0.309^{+0.012}_{-0.012}$	$0.276^{+0.031}_{-0.031}$	$0.274^{+0.074}_{-0.094}$	$0.267^{+0.072}_{-0.094}$	$0.294^{+0.010}_{-0.010}$	$0.269^{+0.012}_{-0.014}$	$0.284^{+0.008}_{-0.008}$	$0.262^{+0.010}_{-0.012}$
σ_8	–	$0.838^{+0.007}_{-0.007}$	$0.725^{+0.140}_{-0.072}$	$0.734^{+0.086}_{-0.170}$	$0.678^{+0.080}_{-0.230}$	$0.830^{+0.007}_{-0.007}$	$0.710^{+0.054}_{-0.045}$	$0.824^{+0.007}_{-0.006}$	$0.702^{+0.049}_{-0.049}$
$\chi^2_{\rm min}/2$	–	5631.59	5631.75	24.06	24.21	5635.52	5631.69	5662.63	5659.82

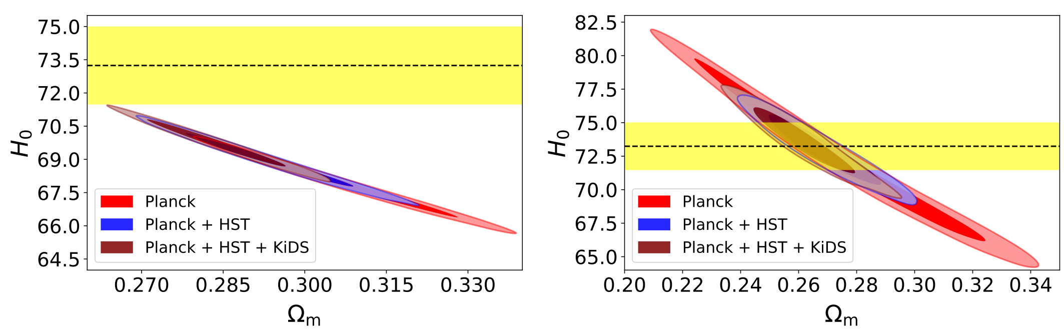

Figure 5.1: Parametric space (68% and 95% CL) in the plane $\Omega_{\rm m} - H_0$ for the ΛCDM (left panel) and IVCDM model (right panel) from three data sets. In the left panel, it is clear to see that the local measurement of $H_0 = 73.24 \pm 1.74$ km s^{-1}Mpc^{-1} (yellow band) is in disagreement with the statistical region of H_0 from the three data sets within the ΛCDM cosmology. In the right panel, we see that there is no tension on H_0 within 68% CL in the IVCDM model.

case of Planck, Planck + HST and Planck + HST + KiDS data[1]. Clearly, the local measurement of H_0 is in disagreement with the region of H_0 predicted by Planck data [43], and other two data combinations within the ΛCDM cosmology. In the right panel of Figure 5.1, the $\Omega_{\rm m} - H_0$ parametric space for the IVCDM model is shown, where one can clearly see that horizontal band showing locally measured range of H_0 is passing through the central region of all contours. Thus, we can conclude that there is no tension on H_0 parameter within IVCDM model. With regard to the tension on σ_8, in the left panel of

[1]We have not shown the $\Omega_{\rm m} - H_0$ statistical region for KiDS data set because it is insensitive to the parameter H_0 [44].

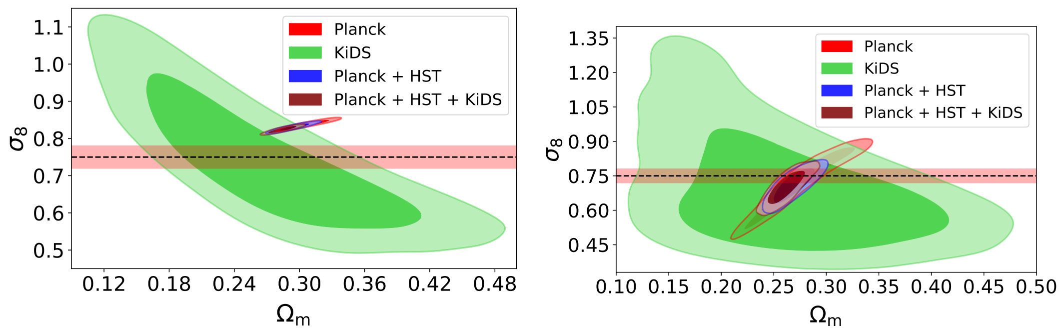

Figure 5.2: Parametric space (68% and 95% CL) in the plane $\Omega_{\rm m} - \sigma_8$ for the ΛCDM (left panel) and IVCDM model (right panel) from four data sets. In the left panel, we see that the $\Omega_{\rm m} - \sigma_8$ region given by the Planck data within the ΛCDM cosmology is clearly in disagreement with the region predicted by KiDS data, as well as with the range given by Planck-SZ (red band). In the right panel for the IVCDM model, we observe that there is no tension on σ_8 within 68% CL.

Figure 5.2, the $\Omega_{\rm m} - \sigma_8$ parametric space is shown for the ΛCDM model with a red band corresponding to the Planck-SZ measurement $\sigma_8 = 0.75 \pm 0.03$ [174]. Clearly, $\Omega_{\rm m} - \sigma_8$ region given by Planck, Planck + HST and Planck + HST + KiDS data within the ΛCDM cosmology is in disagreement with the region predicted by KiDS data, and also with the Planck-SZ measurement of σ_8. In the right panel of Figure 5.2, the $\Omega_{\rm m} - \sigma_8$ parametric space is shown for the IVCDM model, where we observe that there is no tension on σ_8 within 68% CL from Planck data, KiDS data and other two data combinations as well. The tension between the Planck and KiDS data is also quantified by a parameter S_8, that is a combination of σ_8 and $\Omega_{\rm m}$ via the relation $S_8 \equiv \sigma_8\sqrt{\Omega_{\rm m}/0.30}$. One can see from the left panel of Figure 5.3, where the $\Omega_{\rm m} - S_8$ parametric space is shown for the ΛCDM model from the four analyses performed here. Clearly, region given by Planck and Planck + HST data within the ΛCDM cosmology is in disagreement with the region predicted by KiDS data. In the right panel of Figure 5.3, we have shown the same parametric space for the IVCDM model, where we note that there is no tension on S_8, and all these data sets are in agreement with each other. It is important to note that, since the CMB and LSS predictions are not in tension with each other within the IVCDM model, we can use all these data in a joint analysis. In so far discussion, we have shown that the well-known tensions on both the parameters H_0 and σ_8 of ΛCDM model disappear within the framework of

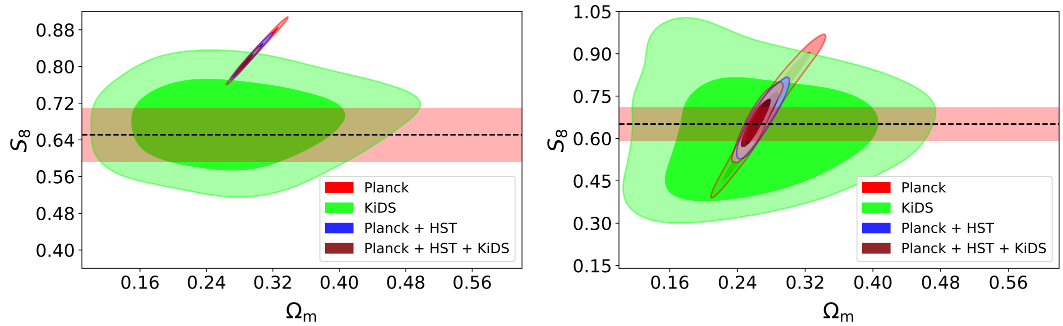

Figure 5.3: Parametric space (at 68% and 95% CL) in the plane $\Omega_{\rm m} - S_8$ for the ΛCDM (left panel) and IVCDM model (right panel) from four data sets. In the left panel, we see that the $\Omega_{\rm m} - S_8$ region given by the Planck data within the ΛCDM cosmology is clearly in disagreement with the region $S_8 \equiv \sigma_8\sqrt{\Omega_{\rm m}/0.30} = 0.651 \pm 0.058$, predicted by KiDS data (red band). In the right panel for the IVCDM model, we observe that there is no tension on S_8 within 68% CL.

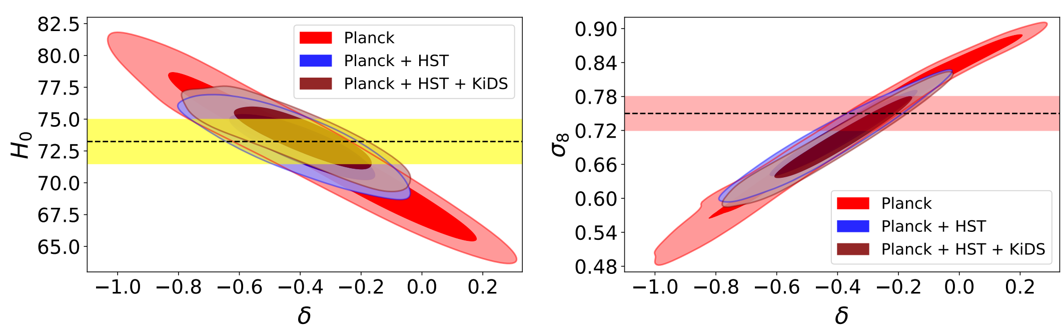

Figure 5.4: $\delta - H_0$ (left panel) and $\delta - \sigma_8$ (right panel) parametric spaces (68% and 95% CL) for the IVCDM model from three data sets. The yellow band corresponds to local value $H_0 = 73.24 \pm 1.74$ km s^{-1}Mpc^{-1} whereas the light red band corresponds to $\sigma_8 = 0.75 \pm 0.03$ by Planck-SZ measurement.

IVCDM model. Next, we focus our attention on the coupling parameter δ. In Figure 5.4, the statistical regions (at 68% and 95% CL) on δ are shown with H_0 and σ_8 from Planck data, and the other two data sets including Planck. We observe that δ finds a negative correlation with H_0 while a positive correlation with σ_8. It amounts to saying that lower values of δ correspond to higher values of H_0 and lower values of σ_8, which is nice with regard to resolving tensions on the both H_0 and σ_8 simultaneously. We have quantified the correlation strength r of δ with H_0 and σ_8 parameters which is shown in Table 5.2 for all the four data sets. We notice very strong correlations of δ with H_0 and σ_8 in case of

Planck data, and two other data combinations with the Planck data. Interestingly, δ shows a strong and positive correlation with σ_8 in case of KiDS data, as well. We find at 99%

Table 5.2: Correlation r of coupling parameter, δ with H_0 and σ_8.

Data	$r_{\delta H_0}$	$r_{\delta\sigma_8}$
Planck	-0.9662	0.9810
KiDS	0.0397	0.7768
Planck + HST	-0.8205	0.9595
Planck + HST + KiDS	-0.8463	0.9672

CL on coupling parameter δ, viz., $-0.34^{+0.59}_{-0.65}$, $-0.23^{+0.72}_{-0.77}$, $-0.40^{+0.35}_{-0.44}$, and $-0.40^{+0.36}_{-0.41}$ for the Planck, KiDS, Planck + HST, Planck + HST + KiDS data, respectively. We notice that the mean values of δ in all cases are negative, indicating the energy/momentum flow from the DM to DE. Clearly, it is reflected by the lower values of fractional matter density, $\Omega_{\rm m}$ in the IVCDM model compared to the ΛCDM model with all data sets displayed in Table 5.1. Further, it is interesting to observe that the non-null range of δ with negative values is up to 99% CL in the joint analyses: Planck + HST + KiDS. Thus, we find a strong statistical support for interaction in the dark sector of the ΛCDM Universe from recent observational data while alleviating both H_0 and σ_8 tensions of the ΛCDM, simultaneously. The IVCDM model is well-behaved both at background and perturbative levels and providing interesting results on H_0 and σ_8 parameters.

5.2.2 Bayesian model comparison

Finally, we perform a statistical comparison of the IVCDM model with standard ΛCDM model by using the well-known information criterion, AIC [68, 69] as discussed in subsection 2.1.4 of Chapter 2.

Table 5.3 summarizes the AIC differences of IVCDM model with reference model (ΛCDM) for the four data combinations. One may notice that in all the analyses performed here, we do not find any strong support in favor of the ΛCDM model. On the other hand, in general, the IVCDM model is penalized in the AIC criterion due to one extra free parameter when compared to the ΛCDM model. Interestingly, it overcomes

Table 5.3: Difference of AIC values of the IVCDM model with respect to reference model (ΛCDM) with all the data combinations used in this work.

Data	ΔAIC
Planck	2.32
KiDS	2.30
Planck + HST	-5.66
Planck + HST + KiDS	-3.62

the said penalty in case of the Planck + HST data, and finds strong preference over the ΛCDM model. Also, we observe a mild preference of the IVCDM model in case of the Planck + HST + KiDS data. Thus, the AIC criterion favors the IVCDM model over the ΛCDM model in the two joint analyses.

5.3 Concluding remarks

In this chapter, we have investigated an extension of the ΛCDM model by allowing interaction between dark sector components of the Universe with the motivation to test the statistical support for interaction from the recent observational data. We have found a possible non-null coupling in the dark sector up to 99% CL in the joint analyses which amount to indicating strong statistical support from the observational data for the dark sector coupling. As a consequence of coupling in the dark sector, we have obtained significantly larger values of H_0 and lower values of σ_8 parameters as compared to the ΛCDM model, with all data sets used in the analysis (see Table 5.1). Thus, we conclude that the simple and minimal extension of the ΛCDM model via a coupling between the dark sector ingredients alleviates the well-known tensions on H_0 and σ_8 parameters of the ΛCDM model, simultaneously with excellent accuracy. Therefore, it is clear that a possible interaction between DM and DE is a viable remedy for the tensions in the cosmological data.