Imprints of interacting dark universe on cosmological perturbations

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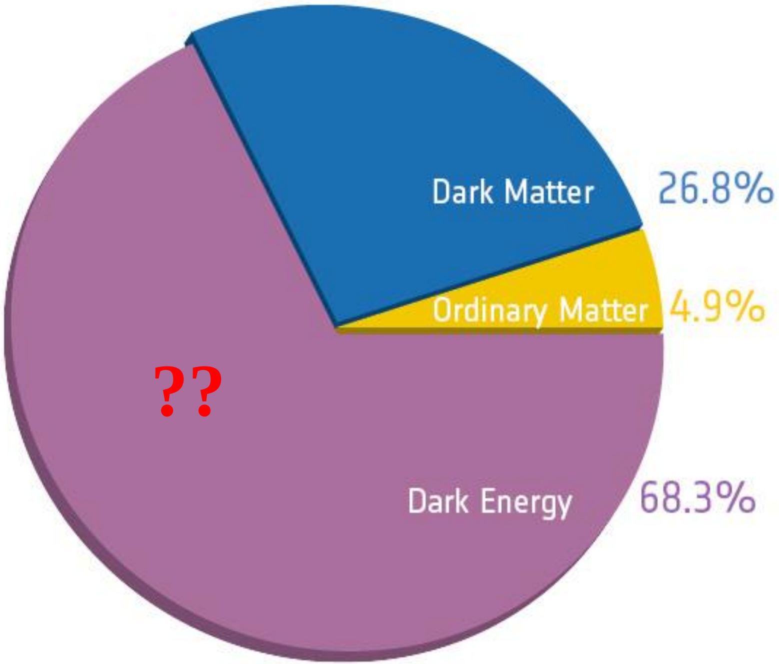
Based on arXiv:2204.05174 and 1805.07148

Cosmic Pie Chart



State of the Art

- Our universe is not only expanding but it is also accelerating!!
- ΛCDM model has been constrained with unprecedented accuracy but is troubled by the 'cosmological constant problem'.
- We need to extent our imagination beyond standard ΛCDM.
- Alternatives ~

  Dynamical DE models (quintessence, k-essence, phantom, chaplygin gas…)

  Modified gravity models (f(R) gravity models, scalar-tensor theories, Gauss-Bonnet gravity…)

Background equations:~

For a spatially flat, homogeneous and isotropic universe, Einstein field equations are given by

$$
\begin{aligned}
3\mathcal{H}^2 &= a^2\kappa\sum_A \rho_A, \\
\mathcal{H}^2 + 2\mathcal{H}' &= a^2\kappa\sum_A p_A,
\end{aligned}
$$

Conformal time is defined as $\tau = \int \frac{dt}{a(t)}$.

$\mathcal{H}(\tau) = \frac{a'}{a}$ is the conformal Hubble parameter.

ρ_A and p_A represent the energy density and pressure of the different components of the Universe.

We have considered only cold dark matter (ρ_c) and dark energy (ρ_{de})components

Conservation equations:

$$
\begin{aligned}
\rho_c' + 3\mathcal{H}\rho_c &= 0, \\
\rho_{de}' + 3\mathcal{H}(1+w_{de})\rho_{de} &= 0.
\end{aligned}
$$

Why DE-DM interaction??

- Provides more general scenario
- Can alleviate cosmological coincidence problem
- The conservation equations gets modified as

$$\rho'_c + 3\mathcal{H}\rho_c = -aQ,$$

$$\rho'_{de} + 3\mathcal{H}(1 + w_{de})\rho_{de} = aQ.$$

- Usually the form of interaction is chosen phenomenologically as

$Q = Q(H\rho_c)$ or $Q = Q(H\rho_{de})$ or combination of both.

DE-DM interaction

We have considered the covariant form of Q^μ as

$$Q^\mu = \frac{\mathcal{H} \rho_{de} u_c^\mu \beta}{a}$$

For homogeneous and isotropic background

$$Q = u_{\mu c} Q^\mu$$

Hence the interaction term can be expressed in the convenient form

$$Q = \frac{\mathcal{H} \rho_{de} \beta}{a}$$

Why this particular form??

B. Wang et al., Rept. Prog. Phys. 79 (9) (2016) 096901; arXiv: 1603.08299

A Toy Model

We have considered the following ansatz:

$$\frac{1}{\rho_{de}}\frac{d\rho_{de}}{da} = -\frac{\lambda a}{(\gamma + a)^2}$$

$$\rho_{de} = A\frac{\exp\left(\frac{-\lambda\gamma}{a+\gamma}\right)}{(a+\gamma)^2}$$

$$V(\phi) \approx A\exp(\alpha_1\phi) + B\exp(\alpha_2\phi)$$

- *Double exponential potentials are well studied in the context of inflation as well as dark energy.*
- *For smaller values of a, it will behave like a ΛCDM model and the deviation from ΛCDM will be prominent at later times*
- *For γ =0, the above equation will provide a simple power law evolution of ρ_{de}*

A Toy Model for interacting case:

We consider the ansatz for the interacting model

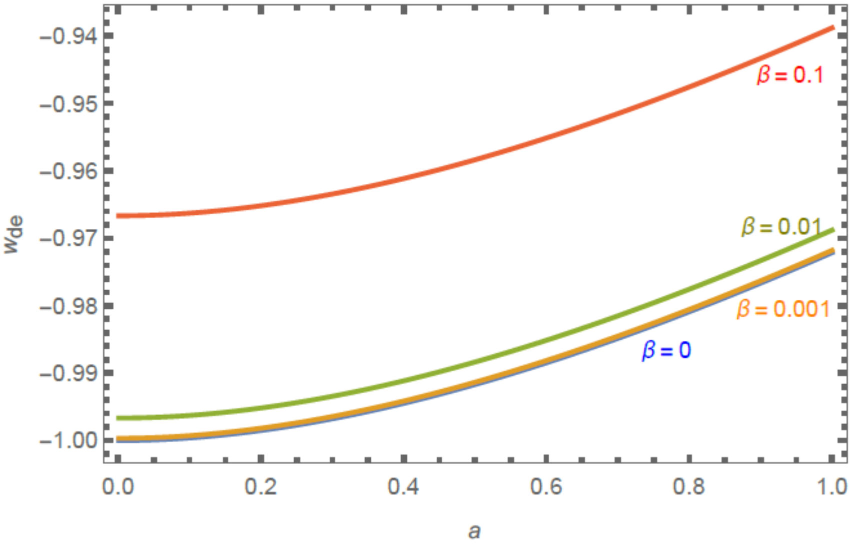
$$\frac{1}{\rho_{de}}\frac{d\rho_{de}}{da} = -\frac{\lambda a}{(\gamma+a)^2}$$

- ***Most of the DE parametrizations considered in literature depicts ΛCDM model at present epoch.***
- ***For smaller values of a, it will behave like a ΛCDM model and the deviation from ΛCDM will be prominent at later times***

$$\frac{\rho'_{de}}{\rho_{de}} = \frac{1}{\rho_{de}}\frac{d\rho_{de}}{d\tau} = -\frac{\lambda a^2 \mathcal{H}}{(\gamma+a)^2}$$

$$w_{de} = -1 + \frac{\beta}{3} + \frac{a^2\lambda}{3(a+\gamma)^2}$$

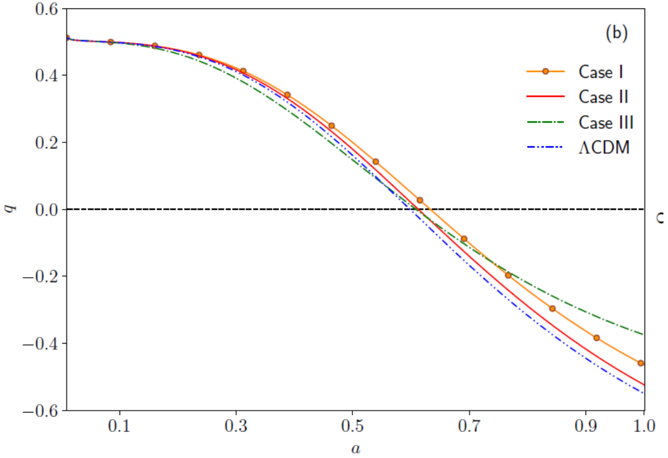
$$w_{de0} = -1 + \frac{\beta}{3} + \frac{\lambda}{3\,[1+\gamma]^2}$$



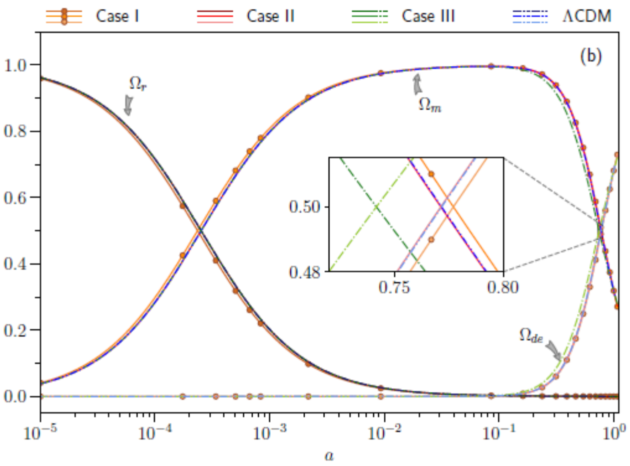
Background and perturbation analyses:

Table 1: Values of parameters used in this work.

Cases	β	λ	γ
Case I	0.10	3.0	5.0
Case II	0.001	0.3	5.0
Case III	0.001	1.0	0.5



Evolution of q is different from ΛCDM model even though wde is close to -1 at the present epoch.



Evolution of perturbations:

- The perturbed FLRW metric in a general gauge in conformal time is

$$ds^2 = a^2(\tau)\{-(1+2\phi)d\tau^2 + 2\,\partial_i B\, d\tau\, dx^i + [(1-2\psi)\delta_{ij} + 2\partial_i\partial_j E]\, dx^i dx^j\}$$

- The perturbation equations in Fourier space for dark matter and dark energy using synchronous gauge are respectively written as

Evolution of perturbations:

•

$$ds^2 \quad \ldots \quad x^i dx^j\}$$

• ... rgy

$$\delta_c' + kv_c + \frac{\mathrm{h}'}{2} = \mathcal{H}\beta\frac{\rho_{de}}{\rho_c}(\delta_c - \delta_{de}),$$

$$v_c' + \mathcal{H}v_c = 0\,,$$

$$\delta_{de}' + 3\mathcal{H}(c_{s,de}^2 - w_{de})\delta_{de} + (1+w_{de})\left(kv_{de} + \frac{\mathrm{h}'}{2}\right)$$

$$+3\mathcal{H}\left[3\mathcal{H}(1+w_{de})(c_{s,de}^2 - w_{de})\right]\frac{v_{de}}{k} + 3\mathcal{H}w_{de}'\frac{v_{de}}{k}$$

$$= 3\mathcal{H}^2\beta(c_{s,de}^2 - w_{de})\frac{v_{de}}{k},$$

$$v_{de}' + \mathcal{H}(1 - 3c_{s,de}^2)v_{de} - \frac{k\,\delta_{de}\,c_{s,de}^2}{(1+w_{de})} = \frac{\mathcal{H}\beta}{(1+w_{de})}\left[v_c - (1+c_{s,de}^2)v_{de}\right]$$

Initial conditions:

- The coupled differential equations are solved with $k = 0.1hMpc^{-1}$ using the publicly available Boltzmann code CAMB after suitably modifying it.

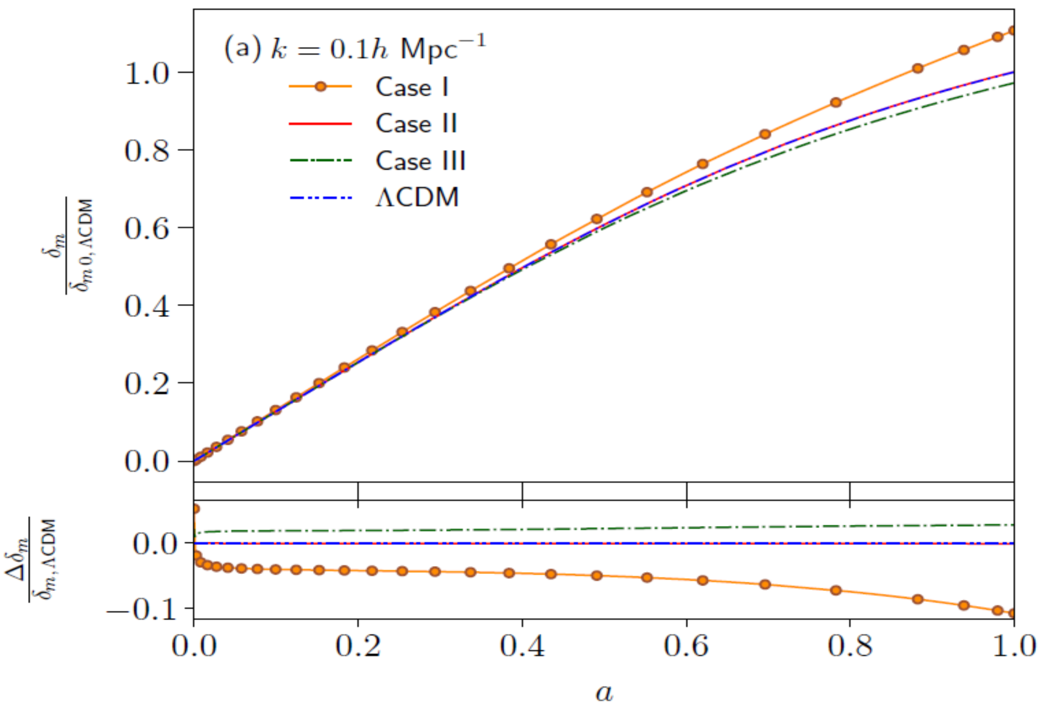
- The adiabatic initial conditions for δ_c, δ_{de} in presence of interaction are respectively

$$\delta_{ci} = \left[3 + \frac{\rho_{de}}{\rho_c}\beta\right]\frac{\delta_\gamma}{3(1+w_\gamma)},$$

$$\delta_{dei} = \left[3\,(1+w_{de}) - \beta\right]\frac{\delta_\gamma}{3(1+w_\gamma)}$$

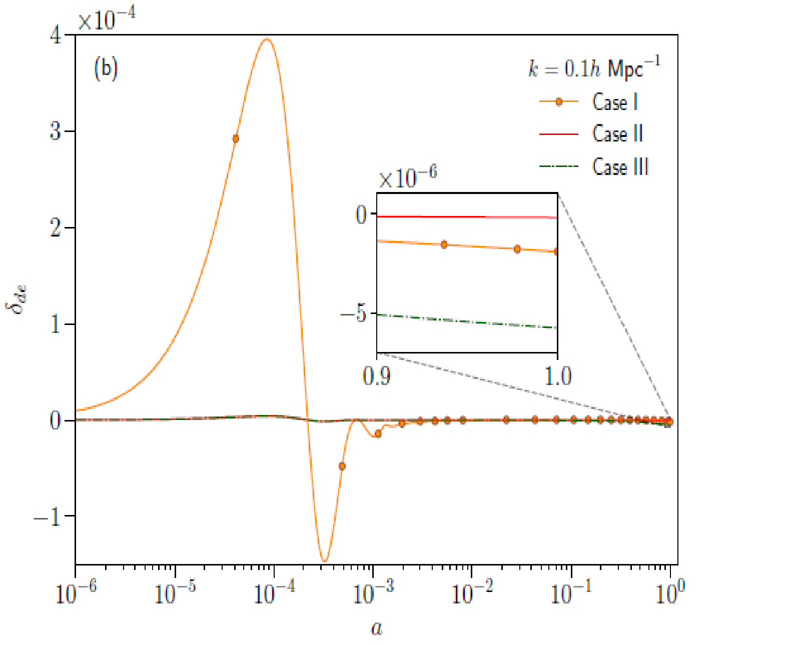
Available at: https://camb.info

Results



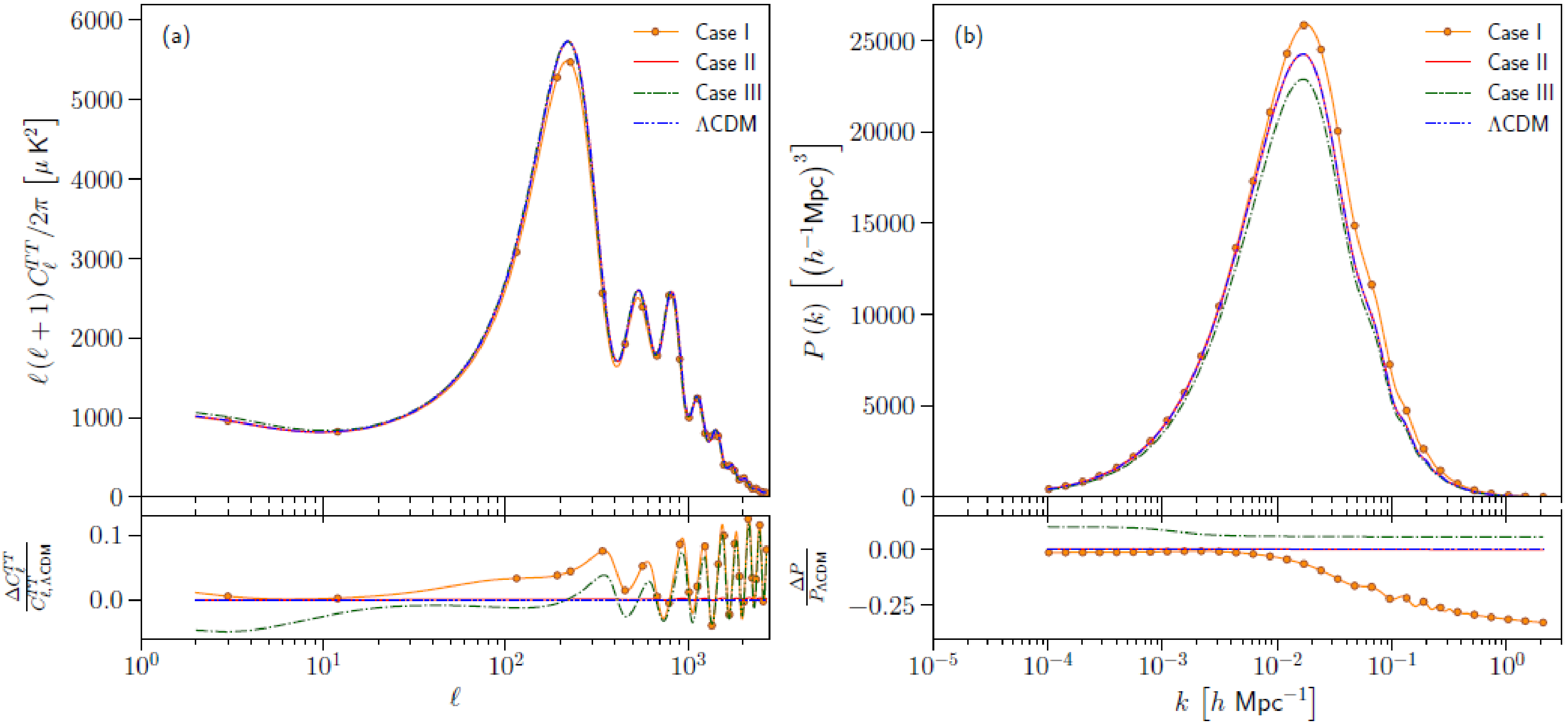
Upper Panel : the matter density contrast $\frac{\delta_m}{\delta_{m0,\Lambda\mathrm{CDM}}}$

Lower Panel : fractional matter density contrast.



Plot of the dark energy density fluctuation, δ_{de} against a

Effect on CMB temperature and matter power spectrum



Numerical Investigation and Observational Constraint

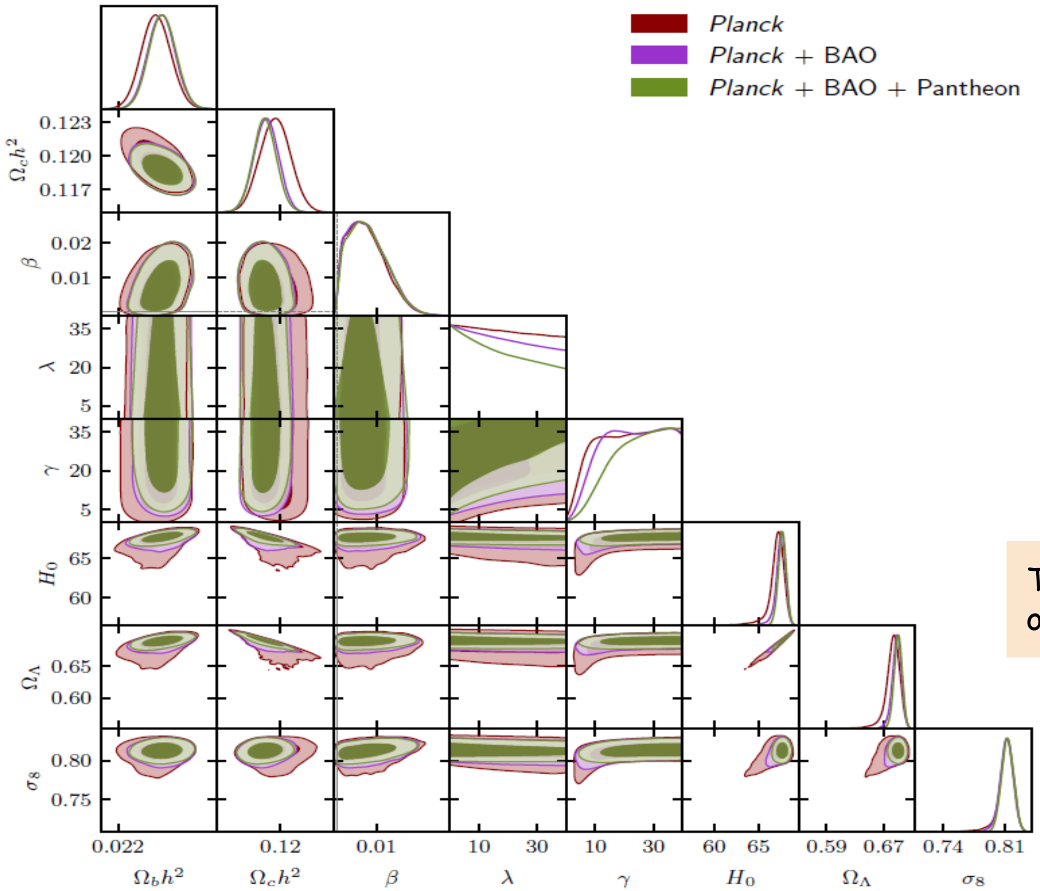
We have considered following data sets:

- CMB : The latest 2018 data release of the Planck collaboration
- BAO (BOSS DR12, 6dFGS, SDSS-MGS)
- Pantheon

Table 2: Prior ranges of nine independent parameters considered in the CosmoMC analysis.

Parameter	Prior
$\Omega_b h^2$	$[0.005, 0.1]$
$\Omega_c h^2$	$[0.001, 0.99]$
$100\theta_{MC}$	$[0.5, 10]$
τ	$[0.01, 0.8]$
β	$[-0.001, 1.0]$
λ	$[0.0, 40.0]$
γ	$[0.0, 40.0]$
$\ln(10^{10} A_s)$	$[1.61, 3.91]$
n_s	$[0.8, 1.2]$

Observational Constraints



Triangular plot of 2D and 1D posterior distribution of different cosmological parameters

Results

Parameter	*Planck*	*Planck* + BAO	*Planck* + BAO + Pantheon
$\Omega_b h^2$	0.022411 ± 0.000157	0.022468 ± 0.000146	0.022479 ± 0.000145
$\Omega_c h^2$	0.11960 ± 0.00120	0.118875 ± 0.000959	0.118764 ± 0.000923
$100\theta_{MC}$	1.040795 ± 0.000315	1.040879 ± 0.000298	1.040886 ± 0.000297
τ	0.05338 ± 0.00724	0.05514 ± 0.00740	$0.05546^{+0.00675}_{-0.00756}$
β	$0.00757^{+0.00276}_{-0.00657}$	$0.00781^{+0.00288}_{-0.00672}$	$0.00790^{+0.00303}_{-0.00661}$
λ	—	—	< 24.6
γ	> 15.9	> 17.3	> 20.7
$\ln(10^{10} A_s)$	$3.0454^{+0.0131}_{-0.0146}$	3.0482 ± 0.0143	3.0485 ± 0.0145
n_s	0.96378 ± 0.00428	0.96540 ± 0.00393	0.96569 ± 0.00393
H_0	$66.94^{+1.02}_{-0.397}$	$67.473^{+0.607}_{-0.412}$	$67.660^{+0.464}_{-0.421}$
Ω_m	$0.31881^{+0.00590}_{-0.0122}$	$0.31197^{+0.00559}_{-0.00710}$	0.31000 ± 0.00571
σ_8	$0.8103^{+0.0102}_{-0.00530}$	$0.81167^{+0.00784}_{-0.00670}$	0.81280 ± 0.00688

Conclusions

- In this work we have revisited the dynamics of the scalar field dark energy models which was allowed to interact with the cold dark matter.
- Perturbative analysis shows that there was no significant effect on the matter density fluctuation for a lower rate of interaction
- With the increase in the strength of interaction of the coupling term, dark energy density fluctuations exhibited visible imprints in the early epochs of evolution.
- We have obtained the central value of the coupling parameter, β to be positive, indicating an energy flow from dark matter to dark energy.
- The parameters λ and γ are not tightly constrained .
- For all the datasets, $\beta = 0$ lies outside the 1σ error region.


Thank you