Perturbations in a dark energy model

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The Universe

- The Universe is described by a spatially flat metric

scale factor

$$ds^2 = -dt^2 + a^2(t)\left(dx^2 + dy^2 + dz^2\right) \qquad a_0 = 1$$

- Large scales $\rightarrow$ larger than the large scale structures $\Rightarrow$ Universe is spatially homogeneous and isotropic
- Size of observable Universe $\sim$ 14 Gpc*, our galaxy $\sim$ 30 Kpc, galaxy cluster $\sim 1 - 10$ Mpc, galaxy super-cluster $\sim$ 100 Mpc
- Small scales ($\lesssim 100 - 300$ Mpc) $\Rightarrow$ Universe is not so uniform $\rightarrow$ start seeing the structures — galaxies, galaxy clusters, voids ...
- Large scale structures evolved from some initial fluctuations
- Evolution of fluctuations depend on background dynamics

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* 1 pc = 3.0857×10^{16} m = 3.26 lightyears

Motivation

- Interaction in the dark sector may not be ruled out *a priori*
- Question: When is the interaction significant in the evolution history of the Universe?
- Possibilities: **(a)** Interaction was there from the beginning of the Universe and exists through its evolution, **(b)** Interaction is a recent phenomenon **(c)** Interaction was entirely an early phenomenon and not at all present today
- An evolving coupling parameter instead of being a constant may answer

To assess if there is any stage of evolution when the interaction is significant

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Interaction In The Dark Sector

$$\rho_c' + 3\mathscr{H}\boxed{\rho_c} = -a\,Q$$

cold dark matter

$Q > 0$: DM $\to$ DE

$$\rho_{de}' + 3\mathscr{H}(1 + w_{de})\boxed{\rho_{de}} = a\,Q$$

dark energy

$Q < 0$: DE $\to$ DM

Interaction In The Dark Sector

$$\rho_c' + 3\mathcal{H}\,\rho_c = -a\,Q$$

cold dark matter

$$\rho_{de}' + 3\mathcal{H}(1+w_{de})\,\rho_{de} = a\,Q$$

dark energy

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

- EoS of DE: $w_{de} = w_0 + w_1(1-a)$
- Ansatz for coupling parameter $\beta(a)$ are :

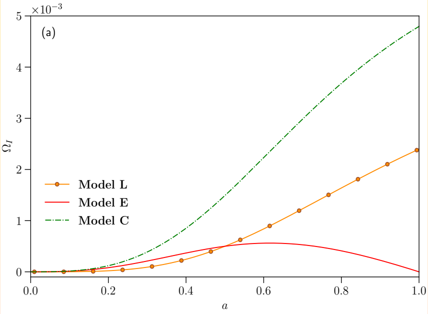
Model L: significant at late time $\Rightarrow$

$$\beta(a) = \beta_0\left(\frac{2a}{1+a}\right)$$

Model E: significant at early time $\Rightarrow$

$$\beta(a) = \beta_0\left(\frac{1-a}{1+a}\right)$$

Model C: a constant $\Rightarrow$ $\beta(a) = \beta_0$



$\Omega_I = \frac{Q}{3H^3/\kappa}$, $w_0 = -0.9995$, $w_1 = 0.005$, $\beta_0 = 0.007$

Evolution of Perturbations

- In synchronous gauge, perturbed metric takes the form

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

- $\psi = \eta$ & $k^2 E = -\mathrm{h}/2 - 3\eta \longrightarrow$ synchronous gauge fields in the Fourier space, $k \rightarrow$ wavenumber
- DM density contrasts $\Rightarrow \delta_c = \delta\rho_c/\rho_c$, DE density contrasts $\Rightarrow \delta_{de} = \delta\rho_{de}/\rho_{de}$
- DM velocity perturbation $\Rightarrow v_c$, DE velocity perturbation $\Rightarrow v_{de}$
- Square of effective sound speed in the rest frame of DE $\Rightarrow c^2_{s,de} = \frac{\delta p_{de}}{\delta\rho_{de}}$

Evolution of Perturbations

- Perturbed energy and momentum conservation equations are

$$\delta_c' + k v_c + \frac{h'}{2} = \mathcal{H}\beta(a)\frac{\rho_{de}}{\rho_c}(\delta_c - \delta_{de})$$

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

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

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

Evolution of Perturbations

- Solved with adiabatic initial conditions
- To avoid the instability in dark energy perturbations $\Rightarrow c^2_{s,de} = 1$
- Matter density contrast $\Rightarrow \delta_m = \frac{\delta\rho_m}{\rho_m} = \frac{(\delta_c\rho_c + \delta_b\rho_b)}{(\rho_c + \rho_b)}$

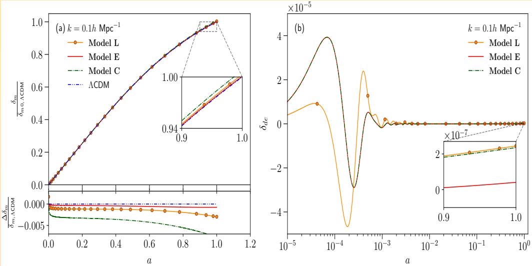
➤ δ_m for Model E evolves close to the ΛCDM model

➤ δ_m for Model L & Model C grow to a little higher value

➤ At early time, δ_{de} oscillates and then decays to very small values

➤ Early time evolution of δ_{de} in Model E is similar to Model C

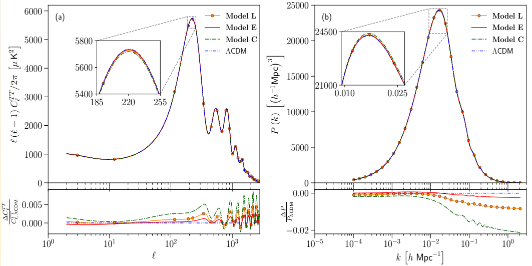
➤ Late time evolution of δ_{de} in Model L is similar to Model C



The origin on the x-axis is actually 10^{-5}

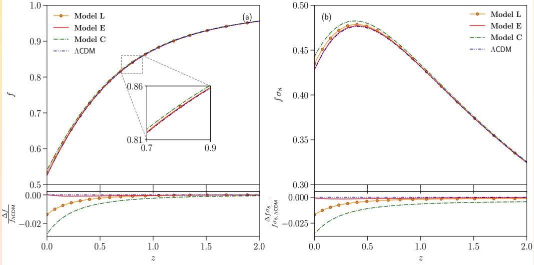
Note: For fractional change, $\Delta\delta_m = (\delta_{m,\Lambda CDM} - \delta_m)$

Power Spectra & Growth Rate



- Lower oscillation amplitudes in $C_\ell^{TT} \rightarrow$ Model C < Model L < Model E < ΛCDM
- Less ISW effect $\rightarrow$ Model C < Model L < Model E < ΛCDM
- Higher $P(k) \rightarrow$ Model C > Model L > Model E > ΛCDM

- Model L & Model C have slightly higher values of $f = \frac{d\ln\delta_m}{d\ln a}$ and $f\sigma_8$ at $z=0$ $(z = \frac{1}{a} - 1)$
- Model E & ΛCDM have same values of f and $f\sigma_8$ at $z=0$
- Model E had a slightly larger value of f and $f\sigma_8$ than ΛCDM, in the recent past



Priors & Datasets

$$\mathscr{P} \equiv \{\Omega_b h^2, \Omega_c h^2, 100\theta_{MC}, \tau, \beta_0, w_0, w_1, \ln\left(10^{10} A_s\right), n_s\}$$

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	[−1.0, 1.0]
w_0	[−0.9999, −0.3333]
w_1	[0.005, 1.0]
$\ln\left(10^{10} A_s\right)$	[1.61, 3.91]
n_s	[0.8, 1.2]

Priors & Datasets

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***Planck*:** CMB anisotropies measurements from *Planck* 2018 collaboration (*Planck* TT, TE, EE + lowE + lensing) (N. Aghanim *et al.*(Planck Collaboration), A&A 2020)

BAO: distance measurements from **(a)** 6dFGS at $z = 0.106$ (F. Beutler, MNRAS 2011), **(b)** SDSS-MGS at $z = 0.15$ (A. J. Ross, MNRAS 2015) & **(c)** DR12 of BOSS-SDSS III at $z = 0.38$, 0.51 and 0.61 (S. Alam *et al.*, MNRAS 2017)

Pantheon: 'Pantheon' catalogue for the luminosity distance measurements of the Type Ia supernovae (SNe Ia) (D. M. Scolnic *et al.*, ApJ 2018)

RSD: $f\sigma_8$ data compilation (S. Nesseris, PRD 2017, B. Sagredo *et al.*, PRD 2018, F. Skara & L. Perivolaropoulos, PRD 2020)

Redshift Space Distortion Data

Survey	z	$f\sigma_8(z)$	Ω_m	Refs.
6dFGS+SnIa	0.02	0.428 ± 0.0465	0.3	(D. Huterer *et al.*, JCAP 2017)
SnIa+IRAS	0.02	0.398 ± 0.065	0.3	(S. J. Turnbull *et al.*, MNRAS 2017, M. J. Hudson *et al.*, ApJL 2012)
2MASS	0.02	0.314 ± 0.048	0.266	(M. Davis *et al.*, MNRAS 2011, M. J. Hudson *et al.*, ApJL 2012)
SDSS-veloc	0.10	0.370 ± 0.130	0.3	(M. Feix *et al.*, PRL 2015)
SDSS-MGS	0.15	0.490 ± 0.145	0.31	(C. Howlett *et al.*, MNRAS 2015)
2dFGRS	0.17	0.510 ± 0.060	0.3	(Y.-S. Song *et al.*, JCAP 2009)
GAMA	0.18	0.360 ± 0.090	0.27	(C. Blake *et al.*, MNRAS 2013)
GAMA	0.38	0.440 ± 0.060		(C. Blake *et al.*, MNRAS 2013)
SDSS-LRG-200	0.25	0.3512 ± 0.0583	0.25	(L. Samushia *et al.*, MNRAS 2012)
SDSS-LRG-200	0.37	0.4602 ± 0.0378		(L. Samushia *et al.*, MNRAS 2012)
BOSS-LOWZ	0.32	0.384 ± 0.095	0.274	(A. G. Sánchez *et al.*, MNRAS 2014)
SDSS-CMASS	0.59	0.488 ± 0.060	0.307115	(C.-H. Chuang *et al.*, MNRAS 2016)
WiggleZ	0.44	0.413 ± 0.080	0.27	(C. Blake *et al.*, MNRAS 2012)
WiggleZ	0.60	0.390 ± 0.063	$\mathbf{C}_{\text{WiggleZ}}$	(C. Blake *et al.*, MNRAS 2012)
WiggleZ	0.73	0.437 ± 0.072		(C. Blake *et al.*, MNRAS 2012)
VIPERS PDR-2	0.60	0.550 ± 0.120	0.3	(A. Pezzotta *et al.*, A&A 2017)
VIPERS PDR-2	0.86	0.400 ± 0.110		(A. Pezzotta *et al.*, A&A 2017)
FastSound	1.40	0.482 ± 0.116	0.27	(T. Okumura *et al.*, PASJ 2016)
SDSS-IV	0.978	0.379 ± 0.176	0.31	(G.-B. Zhao *et al.*, MNRAS 2018)
SDSS-IV	1.23	0.385 ± 0.099	$\mathbf{C}_{\text{SDSS-IV}}$	(G.-B. Zhao *et al.*, MNRAS 2018)
SDSS-IV	1.526	0.342 ± 0.070		(G.-B. Zhao *et al.*, MNRAS 2018)
SDSS-IV	1.944	0.364 ± 0.106		(G.-B. Zhao *et al.*, MNRAS 2018)
VIPERS PDR2	0.60	0.49 ± 0.12	0.31	(F. G. Mohammad *et al.*, A&A 2018)
VIPERS PDR2	0.86	0.46 ± 0.09		(F. G. Mohammad *et al.*, A&A 2018)
BOSS DR12 voids	0.57	0.501 ± 0.051	0.307	(S. Nadathur *et al.*, PRD 2019)
2MTF 6dFGSv	0.03	0.404 ± 0.0815	0.3121	(F. Qin *et al.*, MNRAS 2019)
SDSS-IV	0.72	0.454 ± 0.139	0.31	(M. Icaza-Lizaola *et al.*, MNRAS 2019)

$\Omega_m \longrightarrow$ corresponding fiducial cosmology used to convert redshift to distance

Observational constraints

Presence of interaction for a brief period in the evolutionary history $\Longrightarrow$ **Model E** $\longrightarrow$ describes the evolutionary history of the Universe better than Model L & Model C

Observational constraints

Parameter	*Planck*	*Planck* + $f\sigma_8$	*Planck* + BAO	*Planck* + BAO + Pantheon	*Planck* + BAO + Pantheon + $f\sigma_8$
$\Omega_b h^2$	0.022358 ± 0.000165	0.022490 ± 0.000162	0.022489 ± 0.000156	0.022500 ± 0.000152	0.022546 ± 0.000151
$\Omega_c h^2$	0.12008 ± 0.00126	0.11848 ± 0.00117	0.11850 ± 0.00101	0.118405 ± 0.000970	0.117845 ± 0.000909
$100\theta_{MC}$	1.040769 ± 0.000324	1.040941 ± 0.000318	1.040941 ± 0.000313	1.040945 ± 0.000315	1.040999 ± 0.000313
τ	$0.05466^{+0.00699}_{-0.00779}$	$0.05630^{+0.00703}_{-0.00797}$	$0.05704^{+0.00704}_{-0.00792}$	0.05697 ± 0.00749	$0.05778^{+0.00700}_{-0.00790}$
β_0	0.0339 ± 0.0372	0.0395 ± 0.0381	0.0432 ± 0.0376	0.0448 ± 0.0377	0.0446 ± 0.0370
w_0	< -0.914	< -0.977	< -0.969	< -0.981	< -0.985
w_1	< 0.168	< 0.0645	< 0.0707	< 0.0604	< 0.0489
$\ln(10^{10} A_s)$	3.0486 ± 0.0147	3.0488 ± 0.0148	3.0509 ± 0.0148	3.0507 ± 0.0144	3.0511 ± 0.0146
n_s	0.96315 ± 0.00453	0.96681 ± 0.00434	0.96652 ± 0.00419	0.96672 ± 0.00418	0.96802 ± 0.00404
$H_0 \left[\mathrm{km\ s^{-1} Mpc^{-1}}\right]$	$64.12^{+2.40}_{-1.39}$	$67.00^{+1.02}_{-0.702}$	$66.787^{+0.775}_{-0.600}$	$67.200^{+0.577}_{-0.516}$	67.631 ± 0.516
Ω_m	$0.3492^{+0.0149}_{-0.0282}$	$0.31569^{+0.00834}_{-0.0114}$	$0.31765^{+0.00678}_{-0.00812}$	$0.31353^{+0.00590}_{-0.00658}$	0.30842 ± 0.00588
σ_8	$0.7836^{+0.0221}_{-0.0138}$	$0.80265^{+0.00992}_{-0.00800}$	$0.8019^{+0.0102}_{-0.00866}$	0.80539 ± 0.00830	0.80573 ± 0.00774

☛ 1-D marginalised values with errors at 1σ (68% Confidence Level) for **Model E**

Observational constraints

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- $\beta_0 > 0 \Rightarrow$ Energy flows from DM $\rightarrow$ DE
- For *Planck* data, $\beta_0 = 0$ lies within the 1σ error region
- For other datasets, $\beta_0 = 0$ lies outside the 1σ error region
- w_0 and w_1 are unconstrained

Observational constraints

Parameter	*Planck*	*Planck* + $f\sigma_8$	*Planck* + BAO	*Planck* + BAO + Pantheon	*Planck* + BAO + Pantheon + $f\sigma_8$
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- Derived parameters, H_0, Ω_m and σ_8 are also listed
- For *Planck* data, central value of H_0 is small and error bars are high
- For *Planck* data, σ_8 is skewed towards the galaxy cluster value of $\sigma_8 = 0.77^{+0.04}_{-0.03}$
- Addition of datasets, changes the central values and decreases the error bars

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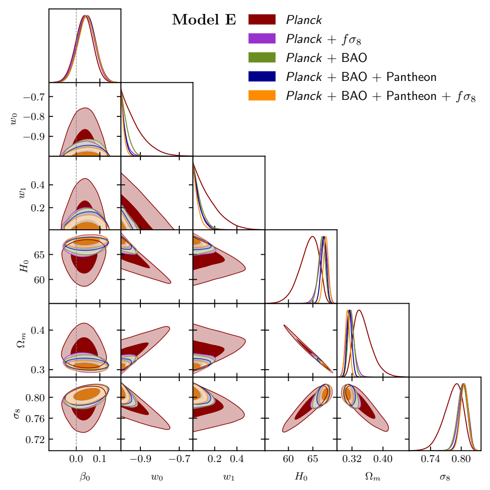
☛ For all the combined datasets, the values shift towards the *Planck* ΛCDM values

Observational constraints



Comparison

Parameter	Model L	Model E	Model C
β_0	0.00788 ± 0.00815	0.0339 ± 0.0372	0.00624 ± 0.00673
w_0	< -0.909	< -0.914	< -0.907
w_1	< 0.174	< 0.168	< 0.174
H_0	$63.98^{+2.45}_{-1.47}$	$64.12^{+2.40}_{-1.39}$	$63.93^{+2.51}_{-1.44}$
Ω_m	$0.3507^{+0.0157}_{-0.0292}$	$0.3492^{+0.0149}_{-0.0282}$	$0.3513^{+0.0153}_{-0.0299}$
σ_8	$0.7825^{+0.0228}_{-0.0141}$	$0.7836^{+0.0221}_{-0.0138}$	$0.7821^{+0.0232}_{-0.0140}$

Compared w.r.t. *Planck* data

- Model L and Model C have very close parameter central values
- Model E has larger β_0 compared to Model L and Model C
- Model E has larger H_0, σ_8 & smaller Ω_m compared to Model L and Model C

Conclusion

From Perturbation Analysis

- Evolution of growth rate, CMB temperature spectrum and matter power spectrum show Model E behaves closely as the ΛCDM model
- Model E performs better than Model L and Model C in describing the evolutionary history of the Universe.

Interaction, if present, is likely to be significant only at some early stage of evolution of the Universe

Thank You

$$\mathbf{C}_{\rm WiggleZ} = 10^{-3} \begin{pmatrix} 6.400 & 2.570 & 0.000 \\ 2.570 & 3.969 & 2.540 \\ 0.000 & 2.540 & 5.184 \end{pmatrix},$$

$$\mathbf{C}_{\rm SDSS\text{-}IV} = 10^{-2} \begin{pmatrix} 3.098 & 0.892 & 0.329 & -0.021 \\ 0.892 & 0.980 & 0.436 & 0.076 \\ 0.329 & 0.436 & 0.490 & 0.350 \\ -0.021 & 0.076 & 0.350 & 1.124 \end{pmatrix}$$

Power Spectra & Growth Rate

$$C_\ell^{TT} = \frac{2}{k}\int k^2 dk\, P_\zeta(k)\Delta^2_{T\ell}(k)$$

$$P(k,a) = A_s k^{n_s} T^2(k) D^2(a)$$

$$f(a) = \frac{d\ln\delta_m}{d\ln a}$$

$$\sigma_8(a) = \sigma_8(1)\frac{\delta_m(a)}{\delta_m(1)}$$

$$f\sigma_8(a) \equiv f(a)\sigma_8(a)$$