No room for Dark Energy Perturbations

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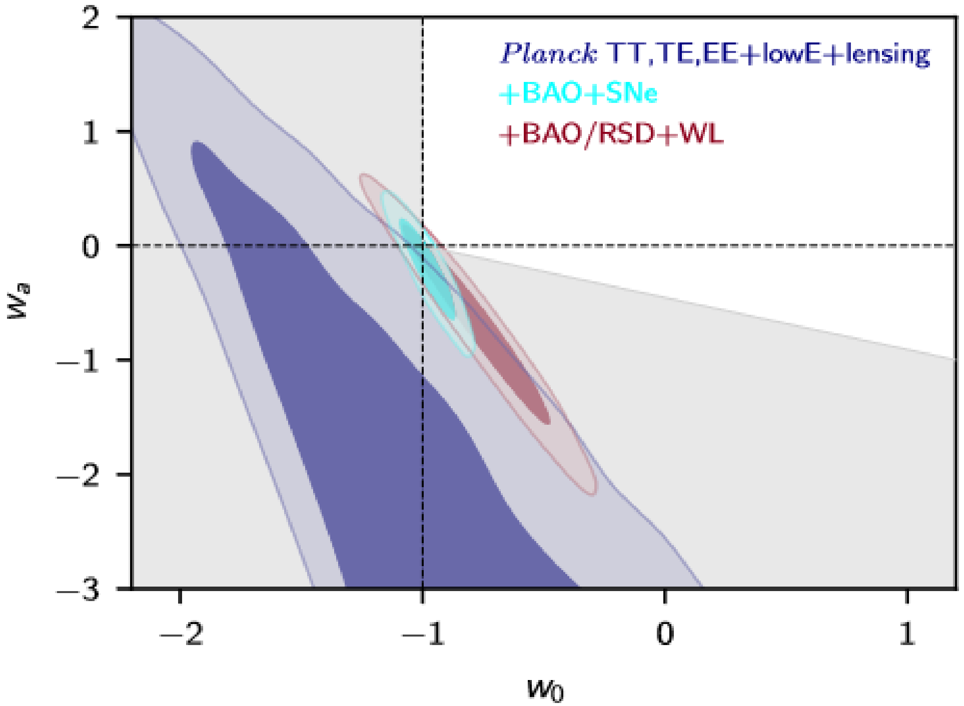
Dark Energy in the Standard cosmological Model

- Responsable for the current accelerated background expansion;
- Allowed EoS parameter space CLOSE to Cosmological Constant;
- NO clustering is assumed!
- Perfect fluid structure (Adiabatic)!
- Effects on Large Scale Structure (LSS) via BACKGROUND ONLY!
- What if not a Cosmological constant?

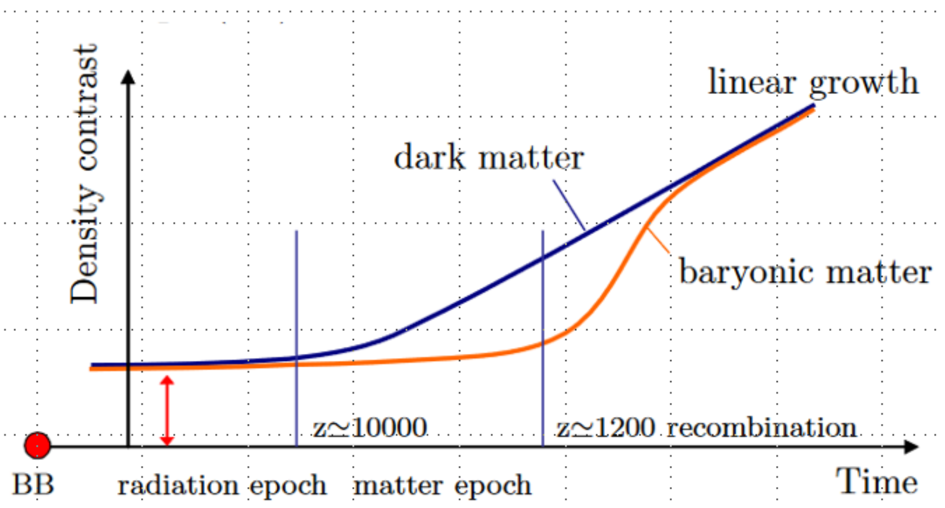


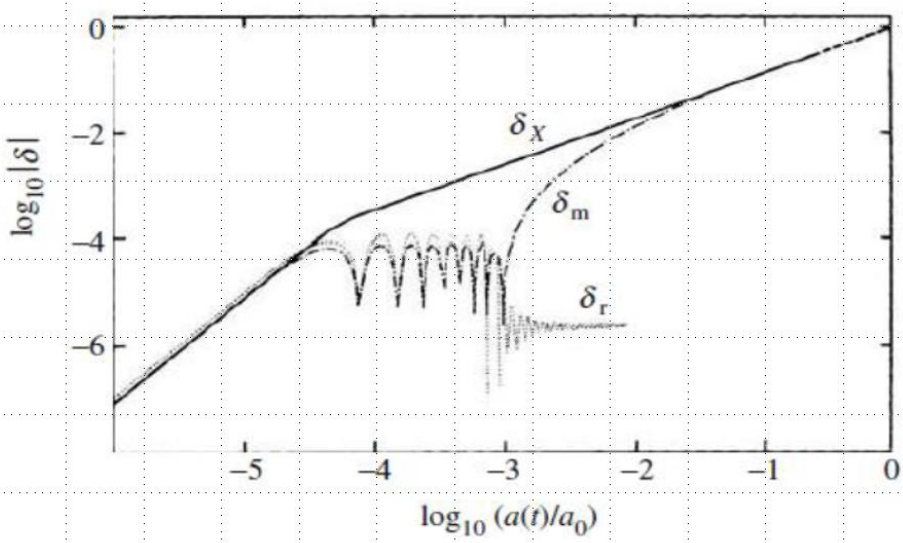
Parameter	*Planck*+SNe+BAO	*Planck*+BAO/RSD+WL
w_0	-0.961 ± 0.077	-0.76 ± 0.20
w_a	$-0.28^{+0.31}_{-0.27}$	$-0.72^{+0.62}_{-0.54}$

Planck 2018 results. VI. Cosmological parameters

arXiv:1807.06209

Growth of matter overdensities





Matter = Dark Matter + Baryonic

Clustering Dark Energy

Effective DE speed of sound

1 - Stays approximately homogeneous

0 - Clusters in a similar fashion to DM

Unconstrained by current data

Mehrabi et al MNRAS (2015)
Hannestad PRD 2005
Bean and Dore PRD 2004

Even so, mild effects observed

Batista &Marra JCAP11(2017)04

DE (entropic) perturbations indeed leave STRONG observational imprints on cosmological observables

PHYSICAL REVIEW D **96**, 083502 (2017)

Revealing the nonadiabatic nature of dark energy perturbations from galaxy clustering data

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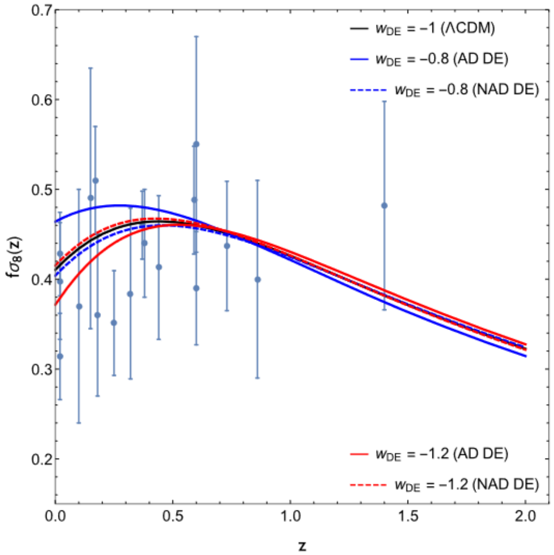
(Received 17 July 2017; published 3 October 2017)

$$\delta p_{\rm nad} = \Omega_{\rm DE}[(-c^2_{\rm a,DE})S + (1 - c^2_{\rm a,DE})\Gamma]\rho.$$



DE (entropic) perturbations indeed leave STRONG observational imprints on cosmological observables

PHYSICAL REVIEW D **97,** 103514 (2018)

Degeneracy between nonadiabatic dark energy models and ΛCDM: Integrated Sachs-Wolfe effect and the cross correlation of CMB with galaxy clustering data

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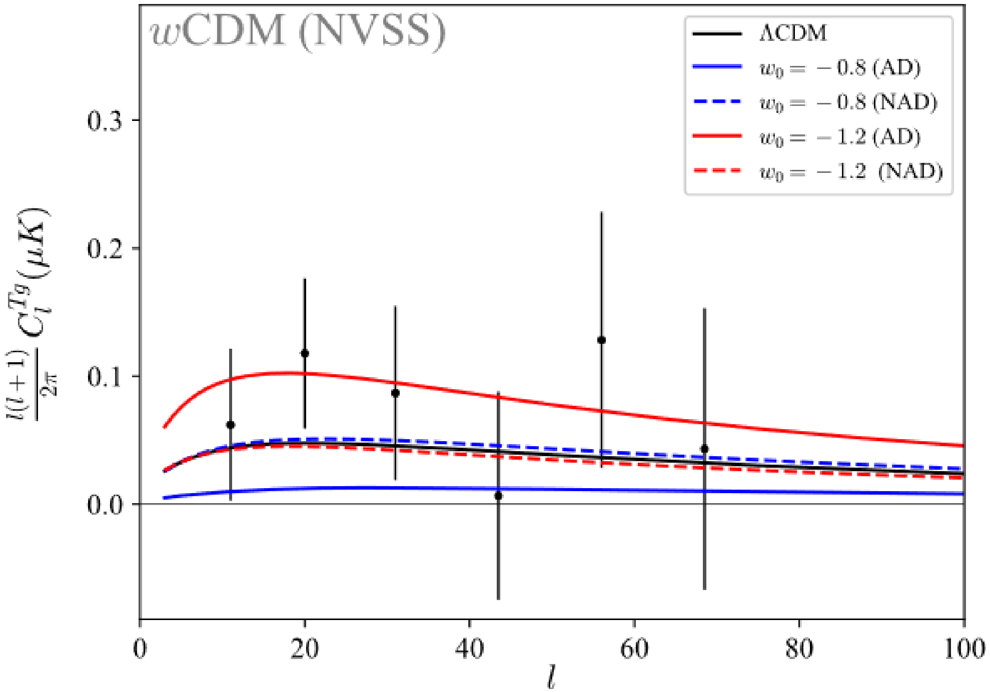

DE (entropic) perturbations indeed leave STRONG observational imprints on cosmological observables

PHYSICAL REVIEW D **101,** 023518 (2020)

Skewness of matter distribution in clustering dark energy cosmologies

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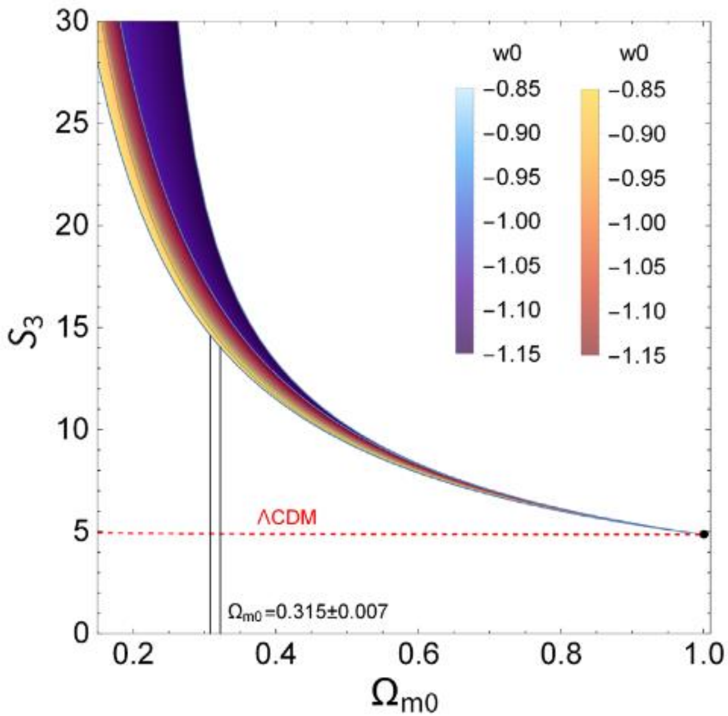
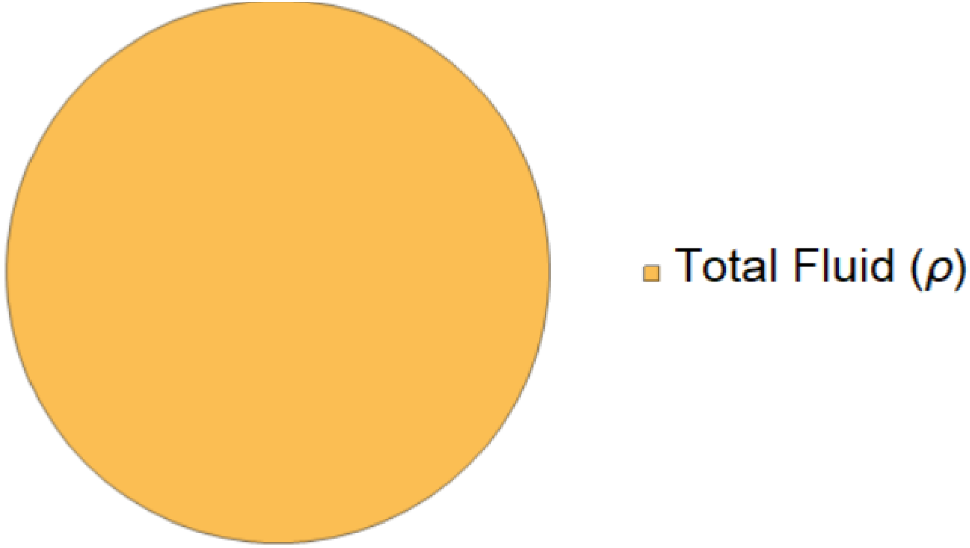


Cosmic medium as a whole

$$T_{ik} = \rho u_i u_k + p h_{ik} \ ,$$

$$h^{ik} = g^{ik} + u^i u^k$$

$$T^{ik}_{\ ;k} = 0$$



Energy Conservation

$$-u_i T^{ik}_{\ ;k} = \rho_{,a} u^a + \Theta \left(\rho + p\right) = 0\,, \qquad \Theta \equiv u^a_{;a},$$

Momentum Conservation

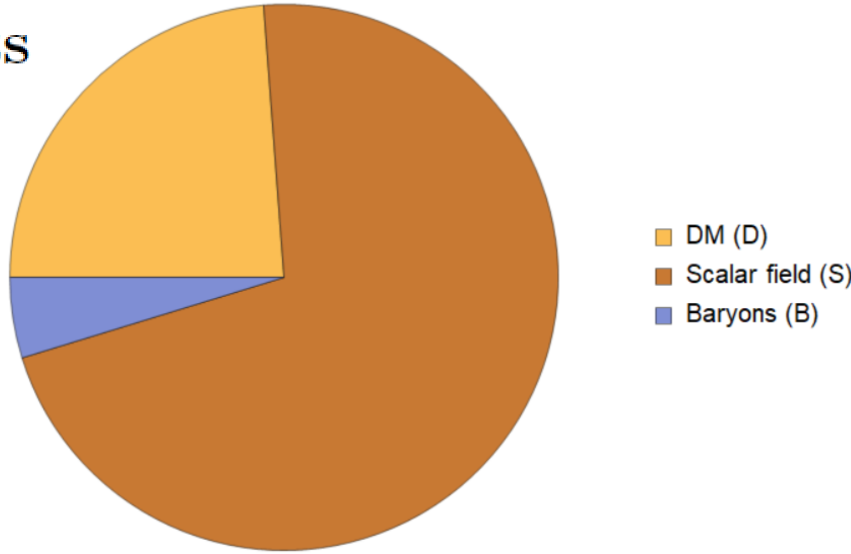
$$h^a_i T^{ik}_{\ ;k} = \left(\rho + p\right) \dot{u}^a + p_{,i} h^{ai} = 0$$

Raychaudury Equation

$$\dot{\Theta} + \frac{1}{3}\Theta^2 - \dot{u}^a_{;a} + 4\pi G \left(\rho + 3p\right) = 0.$$

Decomposition into 3 components

A= { D, S, B }



$$T^{ik} \doteq T_D^{ik} + T_S^{ik} + T_B^{ik}$$

$$T_A^{ik} = \rho_A u_A^i u_A^k + p_A h_A^{ik}, \qquad h_A^{ik} = g^{ik} + u_A^i u_A^k, \qquad u_A^i u_{Ai} = -1,$$

The separate energy conservation equations are $\quad T_A^{ik}{}_{;k} = 0.$

Energy Conservation for each component A

$$-u_{Ai} T_A^{ik}{}_{;k} = \rho_{A,a} u_A^a + \Theta_A \left(\rho_A + p_A\right) = 0\,, \qquad \Theta_A \equiv u_{A;a}^a$$

Momentum Conservation for each component A

$$h_{Ai}^a T_A^{ik}{}_{;k} = \left(\rho_A + p_A\right) u_{A;n}^a u_A^n + p_{A,i} h_A^{ai} = 0.$$

Background dynamics

$$u_C^a = u_S^a = u_B^a = u^a \qquad \text{(background)}$$

CDM is characterized by an EOS parameter: $w_D \equiv p_D/\rho_D$

For the scalar field we use an effective fluid description

$$p_S = \omega_S \rho_S \qquad w_S = w_0 + w_1 (1 - a)$$

Finally, the baryons are modeled as pressureless fluid with an EoS

$$p_B = 0.$$

Background expansion:

$$3H^2 = 8\pi G\rho = 8\pi G (\rho_D + \rho_S + \rho_B)$$

BASIC PERTURBATION RELATIONS

$$ds^2 = -(1+2\phi)\,dt^2 + a^2(1-2\psi)\,\delta_{\alpha\beta}dx^\alpha dx^\beta$$

$$\hat{u}_0 = \hat{u}^0 = \hat{u}^0_A = \hat{u}^0_A = \frac{1}{2}\hat{g}_{00} = -\phi.$$

From the definitions of Θ and the Θ_A one then has

$$\boxed{\hat{u}_\alpha = v_{,\alpha}}$$

$$\hat{\Theta} = \frac{\Delta v}{a^2} - 3\dot{\psi} - 3H\phi$$

and

$$\hat{\Theta}_A = \frac{\Delta v_A}{a^2} - 3\dot{\psi} - 3H\phi,$$

respectively, where Δ is the three-dimensional Laplacian.

First-order dynamics of the total cosmic medium

In terms of the fractional energy-density perturbation $\delta \equiv \frac{\hat{\rho}}{\rho}$

the total first-order energy conservation becomes

$$\dot{\delta} - \Theta\frac{p}{\rho}\delta - \frac{\dot{\rho}}{\rho}\phi + \hat{\Theta}\left(1 + \frac{p}{\rho}\right) + \Theta\frac{\hat{p}}{\rho} = 0.$$

The total momentum balance

$$\dot{v} + \phi = -P^c \equiv \frac{\hat{p}^c}{\rho + p}, \qquad \hat{p}^c \equiv \hat{p} + \dot{p}v.$$

$$-\frac{2}{3}\frac{k^2}{H^2a^2}\psi = \delta^c.$$

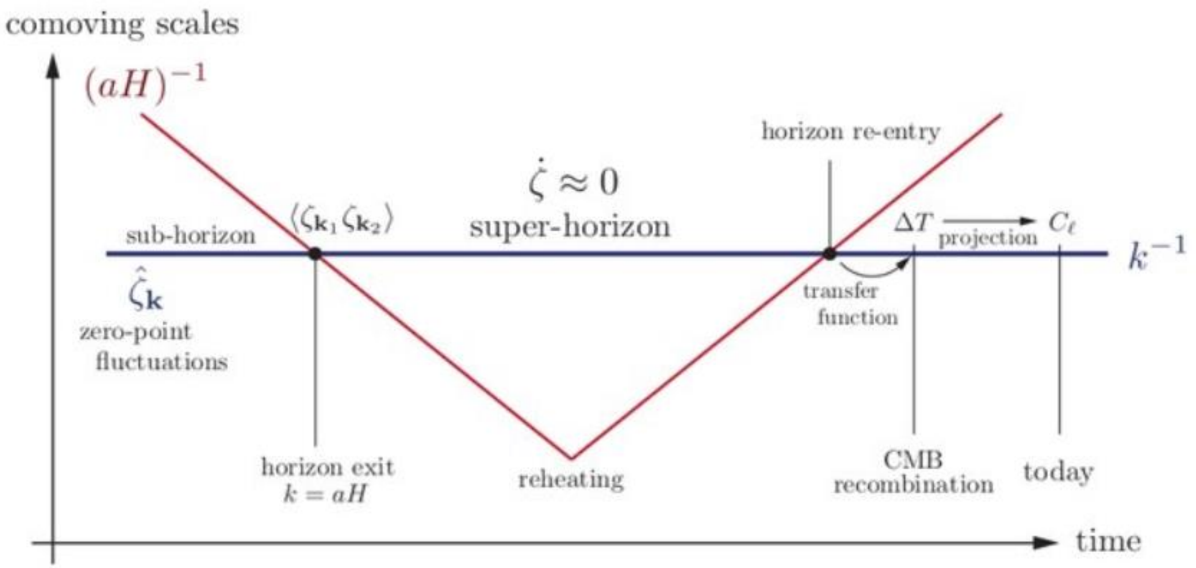
$$\psi = \phi$$

$$\delta^{c\prime\prime} + \left[\frac{3}{2} - \frac{15}{2}\frac{p}{\rho} + 3\frac{p'}{\rho'}\right]\frac{\delta^{c\prime}}{a} - \left[\frac{3}{2} + 12\frac{p}{\rho} - \frac{9}{2}\frac{p^2}{\rho^2} - 9\frac{p'}{\rho'}\right]\frac{\delta^c}{a^2} + \frac{k^2}{a^2H^2}\frac{\hat{p}^c}{\rho a^2} = 0,$$

the comoving density perturbation $\delta^c \equiv \delta + \frac{\dot{\rho}}{\rho}v.$

"Constant curvature perturbation"

It remains constant on a large scale in the absence of any entropy perturbation. This quantity is valuable to cosmological applications, because, for example,it allows one to relate the perturbations generated at a stage of inflation with the primordial perturbations in theearly radiation dominated era.



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Wands&Malik&Lyth&Liddle PRD(2000)

S. M. Leach, M. Sasaki, D. Wands, and A. R. Liddle, Phys. Rev.D64, 023512 (2001)
Weinberg (PRD) 2004

Entropic perturbations

Total Entropic Perturbations = Intrinsic entropy perturbation of each fluid e.g., viscosities + Difference of the dynamical behavior of components

Entropy and energy-density fluctuations are not decoupled.

Entropy perturbations act as a source for density fluctuations

Abboott&Wise Nuc.PB (1984)
Lucchin&MatarresePLB(1985)
Mollerach PRD (1990)

Introducing non-adiabatic perturbations - If the total medium were adiabatic, the pressure perturbations would be given by $\hat{p} = \frac{\dot{p}}{\dot{\rho}}\hat{\rho}$. The difference $\hat{p} - \frac{\dot{p}}{\dot{\rho}}\hat{\rho}$ characterizes deviations from adiabaticity. The total non-adiabatic pressure perturbation can be written in terms of the contributions of the components. The (gauge-invariant) non-adiabatic parts of the component are

$$\hat{p}_{S nad} \equiv \hat{p}_S - \frac{\dot{p}_S}{\dot{\rho}_S}\hat{\rho}_S \, , \qquad \hat{p}_{D nad} \equiv \hat{p}_D - \frac{\dot{p}_D}{\dot{\rho}_D}\hat{\rho}_D .$$

It is convenient to define the (gauge-invariant) relative perturbations

$$S_{BD} \equiv \delta_B - \frac{\delta_D}{1 + w_D}, \quad \delta_B \equiv \frac{\hat{\rho}_B}{\rho_B}, \quad \delta_D \equiv \frac{\hat{\rho}_D}{\rho_D}$$

and

$$S_{BS} \equiv \delta_B - \frac{\delta_S}{1 + w_S}, \quad \delta_S \equiv \frac{\hat{\rho}_S}{\rho_S}.$$

Comoving pressure perturbation

$$\frac{\hat{p}^c}{\rho'} = \frac{p'}{\rho}\delta^c + (1+w_D)\Omega_D P_{Dnad} + (1+w_S)\Omega_S P_{Snad} +$$

$$U\frac{1+w_S}{1+w}\Omega_S S_{BS} + V\frac{1+w_D}{1+w}\Omega_D S_{BD}$$

$$U = \frac{p'_D}{\rho'_D}(1+w_D)\Omega_D - \frac{p'_S}{\rho'_S}(\Omega_B + (1+w_D)\Omega_D)$$

$$V = \frac{p'_S}{\rho'_S}(1+w_S)\Omega_S - \frac{p'_D}{\rho'_D}(\Omega_B + (1+w_S)\Omega_S)$$

$$P_{Dnad} = \frac{\hat{p}_{Cnad}}{\rho(1+w_D)\Omega_D}, \qquad P_{Snad} = \frac{\hat{p}_{Snad}}{\rho(1+w_S)\Omega_S}$$

Dark-sector pressure perturbations

The only step in which a specific choice is made

CDM-Dark Matter

$$\hat{p}_D^{c_D} = 0$$

The CDM pressure perturbations in its rest frame vanishes corresponding to a vanishing effective speed of sound

Scalar Field-Dark Energy

$$\hat{p}_S^{c_S} = \hat{\rho}_S^{c_S}$$

The SF pressure perturbation equals its density perturbation in its rest frame corresponding to a effective speed of sound equals to 1.

Finally, a set of equations has been found

$$S'_{BD} - 3\frac{p'_D}{\rho'_D}\frac{\Omega_B + (1+w_S)\,\Omega_S}{1+w}\frac{S_{BD}}{a} = -3\frac{p'_D}{\rho'_D}\frac{1}{1+w}\left[\frac{\delta^c}{a} + (1+w_S)\,\frac{S_{BS}}{a}\right]$$

$$S'_{BS} + 3\left(1 - \frac{p'_S}{\rho'_S}\right)\frac{\Omega_B + (1+w_D)\,\Omega_D}{1+w}\frac{S_{BS}}{a} = 3\left(1 - \frac{p'_S}{\rho'_S}\right)\frac{1}{1+w}\left[\frac{\delta^c}{a} + (1+w_D)\,\frac{S_{BD}}{a}\right]$$

The total comoving pressure perturbation reduces to

$$\frac{\hat{p}^c}{\rho} = \frac{1+w_S}{1+w}\Omega_S\left(\delta^c + \Sigma\right),$$

with

$$\Sigma \equiv (1+w_D)\,\Omega_D S_{BD} - \left(\Omega_B + (1+w_D)\,\Omega_D\right) S_{BS}.$$

Matter perturbations

$$\delta^{c\prime\prime} + \left[\frac{3}{2} - \frac{15}{2}w + 3\frac{p'}{\rho'}\right]\frac{\delta^{c\prime}}{a} - \left[\frac{3}{2} + 12w - \frac{9}{2}w^2 - 9\frac{p'}{\rho'} - \frac{k^2}{a^2H^2}\frac{1+w_S}{1+w}\Omega_S\right]\frac{\delta^c}{a^2} + \left\{\frac{k^2}{a^2H^2}\frac{1+w_S}{1+w}\Omega_S\Sigma\right\} = 0.$$

SOURCE TERM
(Inhomogeneities)

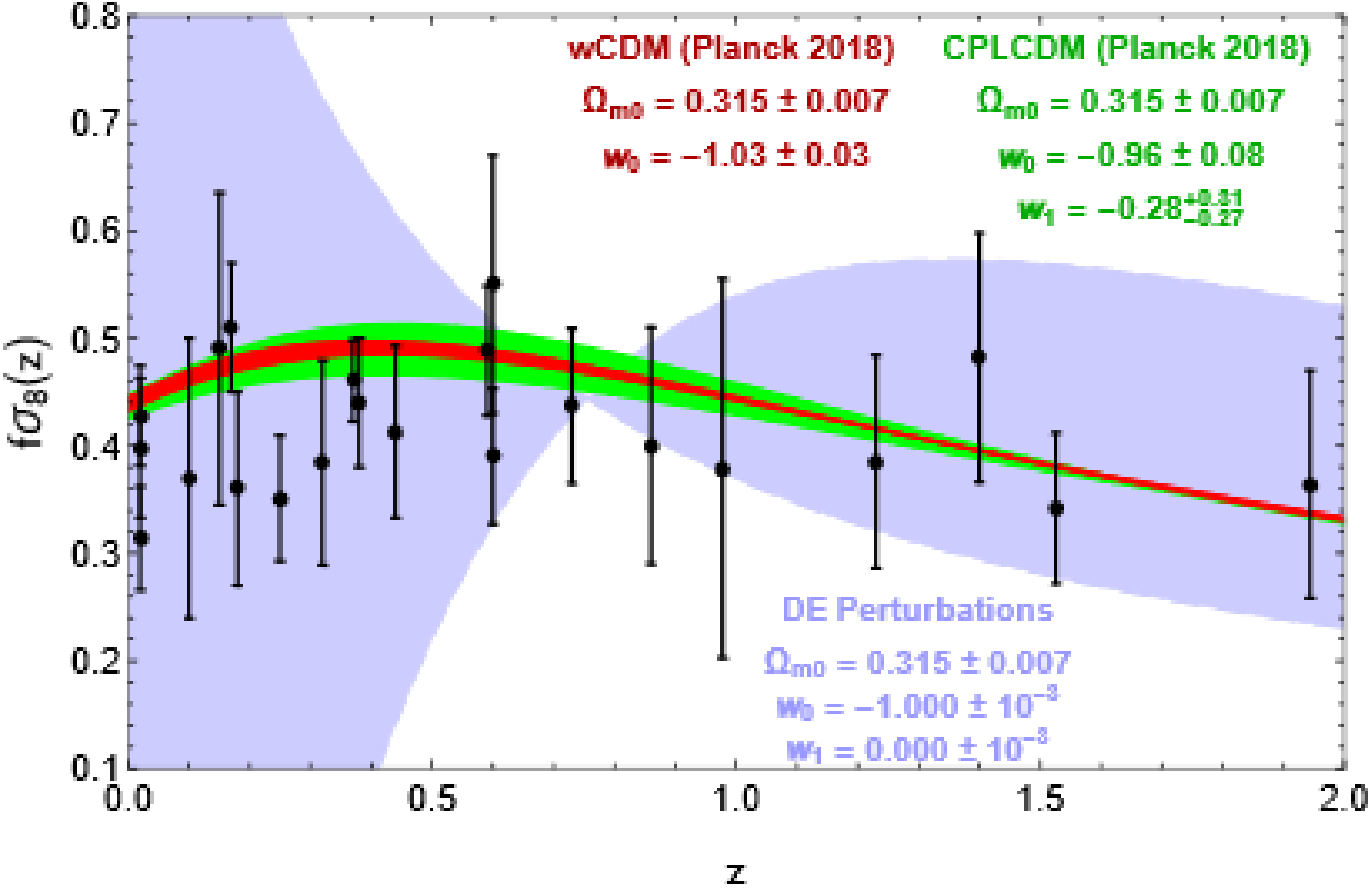
$$\hat{\rho}_B = \hat{\rho} - \hat{\rho}_D - \hat{\rho}_S$$

$$\delta^c_B = \frac{\delta^c + (1+w_D)\,\Omega_C S_{BD} + (1+w_S)\,\Omega_S S_{BS}}{1 + w_D\Omega_D + w_S\Omega_S}$$

Comparing to observations:
(next slide)

$$f\sigma_8(a) = a\frac{\delta'_m(a)}{\delta_m(1)}\sigma_{8,0}$$

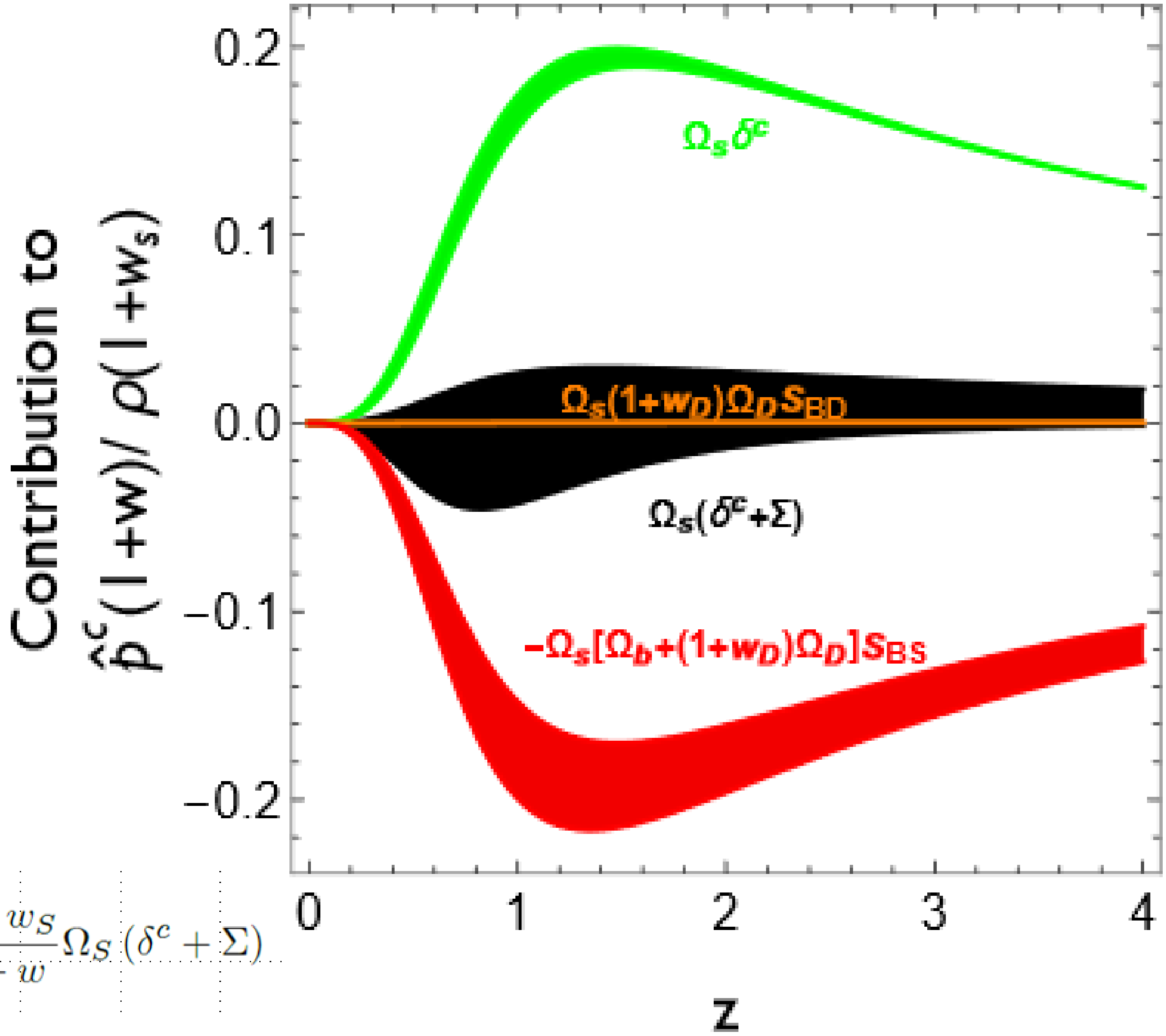
The baryonic growth follows the total matter one



98, no. 8, 083543 (2018) doi:10.1103/PhysRevD.98.083543 [arXiv:1806.10822 [astro-ph.CO]].

Planck 2018 results. VI. Cosmological parameters

arXiv:1807.06209



$$\frac{\hat{p}^c}{\rho} = \frac{1+w_S}{1+w}\Omega_S\left(\delta^c+\Sigma\right)$$

Summary and Conclusions

- A multi-component system manifests intrinsic and *RELATIVE* nonadiabatic features – Such aspects are not taken into accout in standard cosmology;
- Obviously, a genuine cosmological constant indeed does not CLUSTER!
- However, scalar field (SF) representations for the dark energy sector allowing a non-cosmological constant background evolution are capable to source the matter growth!
- WE HAVE SHOWN THAT SUCH NONADIABATIC FEATURES ARE INCOMPATIBLE WITH DATA UNLESS THE DE COMPONENT IS EXACTLY A COSMOLOGICAL CONSTANT; **No time varying DE EoS allowed!**
- Still to be verified: Constraints on DE speed of sound (?)