The effect of dark energy perturbations on the growth of structures

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a BIG problem

SN Type Ia + Cosmological Principle (with Subir's permission)
$\Longrightarrow$ Accelerated expansion

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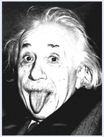
(some) Possible explanations/descriptions

- Cosmological constant :

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G\, T_{\mu\nu}^{(matter)} - \Lambda g_{\mu\nu}$$
$$P = -\rho$$



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(some) Possible explanations/descriptions

- Dark Energy (DE):

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G \, T_{\mu\nu}^{(matter)} + 8\pi G \, T_{\mu\nu}^{(\mathrm{DE})}$$
$$P = w\rho \, , \quad w < -1/3$$

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- Modified Gravity (MG):

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$$= 8\pi G\, T_{\mu\nu}^{(matter)}$$

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Maybe dark matter perturbations help? $\delta = \frac{\delta\rho}{\rho}$

(Huterer, Linder, Maartins, Polarski, ...)

$$\delta_c'' + \mathcal{H}\delta_c' - \frac{3}{2}\mathcal{H}^2\Omega_c\delta_c = 0\,,$$

It seems they can't if the dark energy is a sufficiently general fluid

(Kunz & Sapone, Berstchinger & Zukin)

...But more work is needed.

The growth index

$$\delta_c \propto \frac{1}{a} \exp \int \left(\Omega_c{}^{\gamma} - 1 \right) \mathrm{d} \ln a$$

$$\delta_c'' + \mathcal{H}\delta_c' - \frac{3}{2}\mathcal{H}^2\Omega_c\delta_c = 0 \implies \gamma(w) = 0.55 + 0.05\left[1 + w(z=1)\right] \,, \texttt{Linder}$$

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However... Dark Energy fluctuations!

$$\delta_c'' + \mathcal{H}\delta_c' - \frac{3}{2}\mathcal{H}^2\Omega_c\delta_c = \frac{3}{2}\mathcal{H}^2\Omega_x\left[\left(1 + 3\hat{c}_s^2\right)\delta_x + 9\left(1 + w\right)\mathcal{H}\left(\hat{c}_s^2 - w\right)\frac{\theta_x}{k^2}\right]$$

$$\delta_x'' = f\left(\delta_x', \delta_x, \delta_c', \delta_c\right), \quad \theta_x = \theta_x\left(\delta_x', \delta_x, \delta_c'\right)$$

$$c_s^2 = \frac{\delta P_x}{\delta \rho_x}, \quad \text{speed of sound of DE}$$

No gravitational potentials

The growth index

$$\delta_c \propto \frac{1}{a} \exp \int \left({\Omega_c}^{\gamma} - 1 \right) \mathrm{d} \ln a$$

$$\gamma = \gamma \left(w, \hat{c}_s^2, k, z, \Omega_c^{(0)} \right)$$

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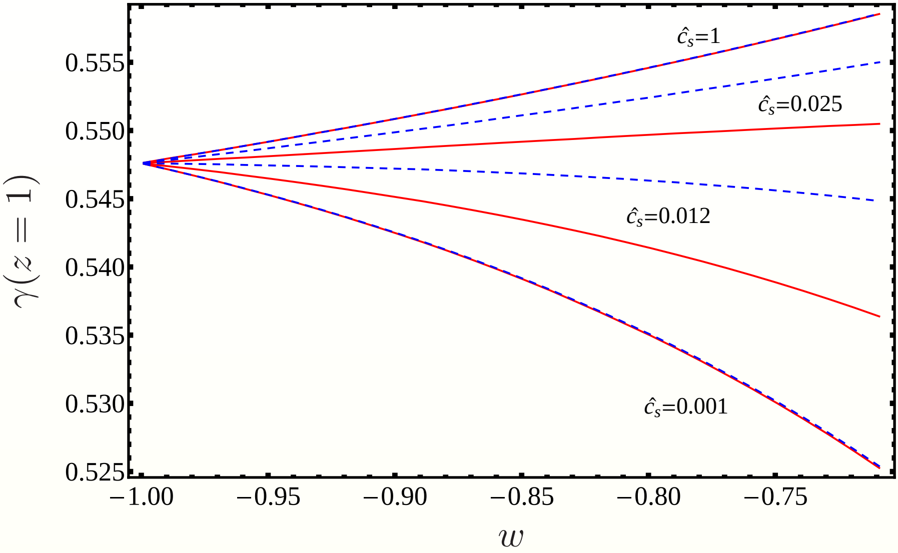
Required for consistency (dynamically generated)... Even if $w = -1$ (!)

Growth index as a function of w



State of the art concerning γ

Theory

- Different gravity theories ($f(R)$, DGP, GR. . .) predict different values
- But is seems that the results can be mimicked with a general DE fluid
- We devised a parameterization to include DE perturbations (assumptions: Constant w and $\hat{c}_s^2$, no shear)

Experiment

- Current data (BAO, WL, LSS, X-ray clust., Lyman–α, ISW) still poor.
- Accuracy of future experiments $\Delta\gamma \simeq 0.04 \to 7\%$. . .
- Effect of DE perturbations also can be as large as $\Delta\gamma$ at any redshift.
- Accuracy forecasts should be clarified with DE perturbations included

Conclusion and results

1. Dark energy perturbations are needed for consistency
2. The growth index γ depends on
   - equation of state of DE, w
   - comoving scale, k (From Fourier space)
   - speed of sound of DE, c_s^2
   - redshift, z. The dependence is affine ("linear")
   - amount of dark matter, Ω_c^0
3. We have designed a parameterization of γ in terms of these variables. (Long, I didn't show it) 0.2% or better! precision
4. Including DE perturbations the variation in γ is comparable with the accuracy forecasts for the next generation of observations $\sim 7\%$

Will we measure DE fluctuations ?