Dark energy constraints using matter density fluctuations

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Dark energy and the "cosmological constant problem"

Recent observations indicate a "dark energy" $\rho_\Lambda^{\rm hoje} \approx 0.7\rho_c^0 \sim 10^{-121}\, M_{\rm Pl}^4$.

However, there is a big discrepancy when we compare with $\rho_{vac} = \frac{\Lambda}{(8\pi G)},$ where $M_{Pl} = 1/8\pi G = 2.44 \times 10^{18} GeV$ is the reduced Planck mass.

Actually, if we suppose $M_{\rm SUSY} \sim 10^{16}\,{\rm GeV}$: $\rho_{\rm vac} \simeq M_{\rm SUSY}^4 \sim 10^{-12} M_{\rm Pl}^4$.

Λ=constant (ΛCDM) problems:

1. **Old problem:** Why $\rho_\Lambda^{\rm hoje}$ is so small?

2. **Coincidence problem:** Why $\rho_\Lambda^{\rm hoje}$ has the same order of $\rho_M^{\rm hoje}$? Why now?

Dark energy models constrained using matter density fluctuations:

1. A FLRW model with a running Λ [$\Lambda(t)$CDM];

2. The $\Lambda(t)$CDM with a extra X component [$\Lambda(t)$XCDM].

Linear dark matter and dark energy densities perturbations

We should consider simultaneous perturbations in:

$$\rho_N \to \rho_N + \delta\rho_N \,, \qquad p_N \to p_N + \delta p_N \,, \qquad g_{\mu\nu} = g^B_{\mu\nu} + h_{\mu\nu} \qquad U^\mu_N \to U^\mu_N + \delta U^\mu_N \,,$$

with a *gauge invariant non adiabatic pressure perturbation:*

$$\delta p_D = c_s^2 \delta\rho_D + 3Ha^2(1 + w_e)\rho_D(c_s^2 - c_a^2)\frac{\theta_D}{k^2} \,, \qquad (1)$$

where c_s^2 is the effective and c_a^2 is the *adiabatic sound velocity*

$$c_a^2 \equiv \frac{p'_D}{\rho'_D} = w_e - \frac{a}{3}\frac{w'_e}{(1 + w_e)}$$

[H. Kodama, M. Sasaki, Prog. Theor. Phys. 1984]

in terms of the dark energy *effective equation of state* (EOS)

$$w_e \equiv \frac{p_D}{\rho_D}.$$

Dark matter and dark energy fluctuations

The perturbed equations

$$\delta_M' = -\frac{1}{aH}\left(\theta_M - \frac{\hat{h}}{2}\right) ,$$

$$\delta_D' = -\frac{(1+w_e)}{aH}\left\{\left[1 + \frac{9a^2H^2(c_s^2 - c_a^2)}{k^2}\right]\theta_D - \frac{\hat{h}}{2}\right\} - \frac{3}{a}(c_s^2 - w_e)\delta_D ,$$

$$\theta_M' = -\frac{2}{a}\theta_M ,$$

$$\theta_D' = -\frac{1}{a}\left(2 - 3c_s^2\right)\theta_D + \frac{k^2}{a^3H}\frac{c_s^2\delta_D}{(1+w_e)} ,$$

$$\hat{h}' + \frac{2}{a}\hat{h} - \frac{3H}{a}\tilde{\Omega}_M\delta_M = \frac{3H}{a}\tilde{\Omega}_D\left[(1+3c_s^2)\delta_D + 9a^2H(c_s^2 - c_a^2)\frac{\theta_D}{k^2}\right] ,$$

where $\hat{h} \equiv \frac{\partial}{\partial t}\left(\frac{h_{ii}}{a^2}\right)$ and $\theta_N \equiv \nabla_\mu(\delta U_N^\mu) = \nabla_i(\delta U_N^i)$, diverge for

$$w_e \rightarrow -1(\rho_D \neq const.) \qquad and \qquad c_a^2 < 0.$$

Neglecting dark energy fluctuations $\delta_D \equiv \delta\rho_D/\rho_D \approx 0$

The growth of the matter fluctuations $\mathcal{G}(a) \equiv \delta_M(a)/a$

$$\mathcal{G}''(a) + \left[\frac{7}{2} - \frac{3}{2}\,\frac{w_e(a)\,r(a)}{1+r(a)}\right]\frac{\mathcal{G}'(a)}{a} + \frac{3}{2}\,\frac{[1-w_e(a)]\,r(a)}{1+r(a)}\,\frac{\mathcal{G}(a)}{a^2} = 0 \qquad (2)$$

is scale independent (k).

The linear scale independent "bias" parameter

$$b^2 = P_{GG}/P_{MM} \propto P_{GG}/(\delta\rho_M/\rho_M)^2 \qquad (3)$$

should be close to 1 when the galaxies had time enough to correlate with the mass distribution of the Universe.

(P_{GG} is given by LSS data and $P_{MM} \propto a^2\,\mathcal{G}^2(a)$ is model dependent).

The successful standard ΛCDM model predicts $b_\Lambda(0)^2 \simeq 1$ ($\sim$ 10% accuracy)

[S. Cole et al, MNRAS 2005]

The FLRW model with variable $\Lambda(t)$

The Friedmann equation is given by:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\rho_M + \rho_\Lambda)\,, \qquad (4)$$

where ρ_Λ is motivated by quantum field theory

$$\rho_\Lambda \equiv \rho_\Lambda(t) \,=\, \rho_\Lambda^0 + \frac{3\,\nu}{8\pi}\,M_P^2\,\left(H^2 - H_0^2\right)\,. \qquad (5)$$

Energy exchange between the vacuum and matter sectors

$$\dot{\rho}_M + \dot{\rho}_\Lambda = -3H\rho_M\,. \qquad (6)$$

[I.L. Shapiro, J. Solà, JHEP 2002; PLB 2000]

The dimensionless parameter ν is defined by

$$\nu \equiv \frac{\sigma}{12\,\pi}\,\frac{M^2}{M_P^2}\,, \qquad (7)$$

M is the effective mass of the heavy particles, bosons/fermions ($\sigma = \pm 1$)

$$M = M_{Pl} \to \nu \equiv \nu_0 \simeq 2.6 \times 10^{-2}\,. \qquad (8)$$

The ΛXCDM model

The total “dark energy" is composed by:

$$\rho_D = \rho_\Lambda + \rho_X \,, \qquad p_D = p_\Lambda + p_X \,, \tag{9}$$

where $\rho_\Lambda = \rho_\Lambda(t)$ e $\rho_X = \rho_X(t)$ is a “cosmon" component.

[J. Grande, J. Solà, H. Štefančić, JCAP 2006]

The component X is obtained from the total dark energy conservation law

$$\dot{\rho}_X + \dot{\rho}_\Lambda = -3H(1 + w_X)\rho_X \,, \tag{10}$$

where w_X is the EOS of the “cosmon"

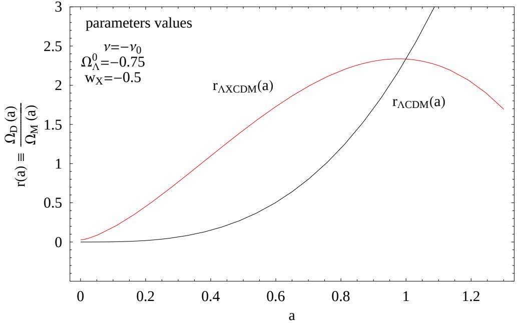
$$w_X \equiv \frac{p_X}{\rho_X} \,. \tag{11}$$

w_X is considered in one of the following ranges:

$-1 < \omega_X < -1/3$ (quintessence-like cosmon) or
$\omega_X < -1$ (phantom-like cosmon).

The ΛXCDM and the coincidence problem

The total DE density varies in such way that the ratio $r(a) \equiv \Omega_D/\Omega_M$ can be bounded due to the existence of a maximum



where the Universe stops expanding

$$r(a) = \left[\frac{1-\Omega_\Lambda^0}{\Omega_M^0\,(1-\nu)} - \frac{w_X}{w_X-\epsilon}\right] a^{-3(w_X-\epsilon)} + \frac{(\Omega_\Lambda^0-\nu)\,a^3}{(1-\nu)\,\Omega_M^0} + \frac{\epsilon}{w_X-\epsilon}\,, \quad (12)$$

where $r_0 = \Omega_D^0/\Omega_M^0 = 0.7/0.3 \simeq 2.33$ and $\epsilon \equiv \nu(1+w_X)$.

“F-test"

We applied the following test

$$|F| \equiv \left|1 - \frac{b^2(z)}{b_\Lambda^2(z)}\right|_{z=0} = \left|1 - \frac{\mathcal{G}_\Lambda^2(z)}{\mathcal{G}^2(z)}\right|_{z=0} \leq 0.1\,, \tag{13}$$

to the $\Lambda(t)$CDM models, predicting

$$|\nu| \lesssim 0.05\nu_0 \simeq 10^{-3}, \tag{14}$$

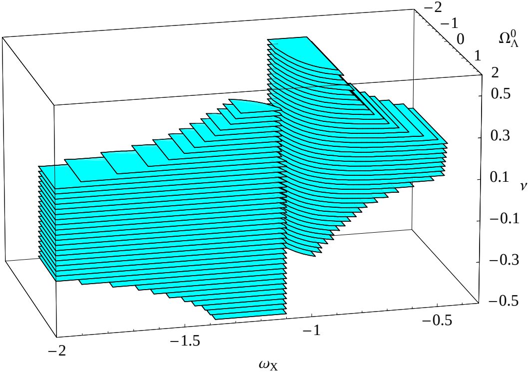
which is in agreement with different methods and authors.

[J. Grande, R. Opher, A. Pelinson, J. Solà, JCAP 2007]

This condition further constraints the limited 3D region in the parameter space $(\Omega_\Lambda^0,\, w_X,\, \nu)$ of the ΛXCDM model associated with restrictions of nucleosynthesis plus solution of the coincidence problem.

3D-region in the parameter space $(\Omega_\Lambda^0,\, w_X,\, \nu)$ for $\Omega_M^0 \simeq 0.3$

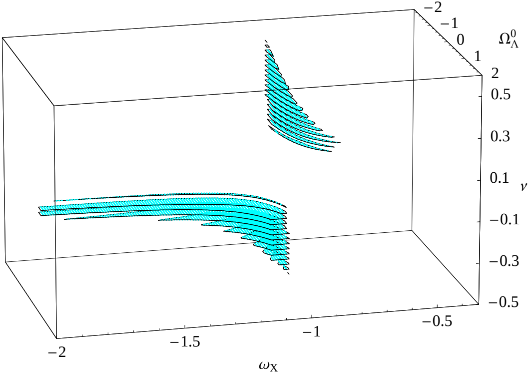
Constraints using nucleosynthesis plus the two restrictions associated with the solution of the coincidence problem gives:



[J.Grande, J.Solà and H.Štefančić, JCAP 2006]

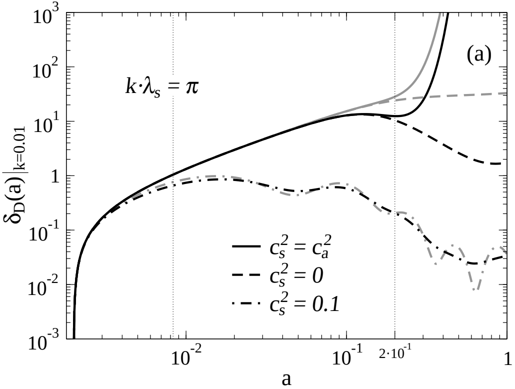
New 3D-region in the parameter space $(\Omega_\Lambda^0,\ w_X,\ \nu)$

Volume of points allowed by nucleosynthesis bound, “coincidence problem" conditions, together with the effective EOS restrict to $|1+\omega_e(0)| \leq 0.3$ and the “F-test"



[J. Grande, R. Opher, A. Pelinson, J. Solà, JCAP 2007]

Adiabatic ($c_s^2 = c_a^2 < 0$) and non-adiabatic $0 \leq c_s^2 \leq 1$) perturbation

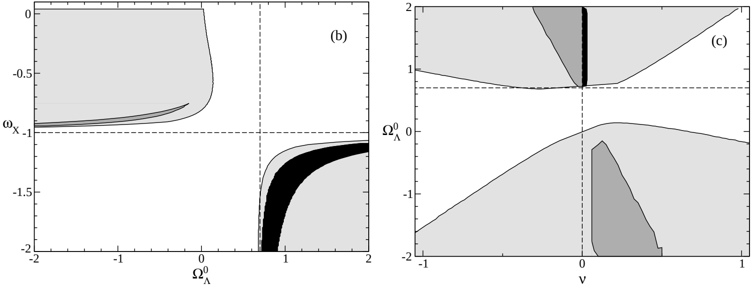


The adiabatic perturbations diverge for

$$c_s^2 = c_a^2 = \frac{\Omega_X^0}{\Omega_X(a)}(1+b)(\omega_X - \epsilon)\ a^{-3(1+\omega_X-\epsilon}<0.$$

and when $b \equiv -\frac{\nu\,\Omega_M^0}{(\omega_X-\epsilon)\,\Omega_X^0} < 0$ (at the crossing $w_e(a) = -1$).

Further constraints in the 3D region of the parameter space



Projections without divergence in δ_M.
Allowed region gives ($w_X < -1$ and $\Omega^0_\Lambda > 0.7$) $\Rightarrow \Omega^0_X = 0.7 - \Omega^0_\Lambda < 0$:

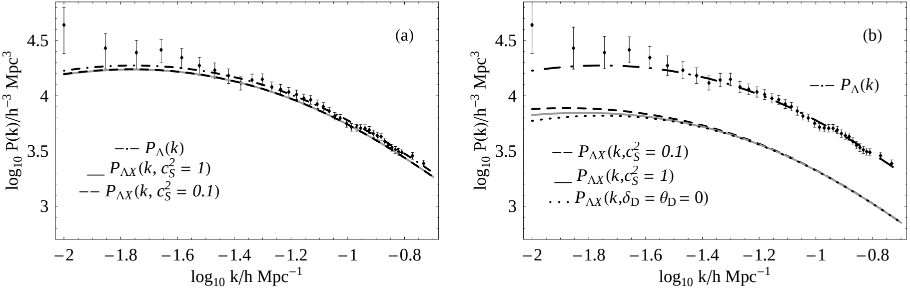
$$(1 + w^0_e)\,\Omega^0_D = (1 + \omega_X)\,\Omega^0_X \qquad \Rightarrow \qquad -1 < w^0_e < -1/3\,.$$

Final conclusion:

The total DE density ρ_D behaves effectively as quintessence.

[J. Grande, A. Pelinson, J. Solà, arXiv:0904.3293]

Matter power spectrum



$$\Omega_M^0 = 0.3, \Omega_\Lambda^0 = 0.8, \nu = \nu_0 \equiv 2.6 \times 10^{-2}, w_X = -1.6; (c_S^2 = 0.1; 1)$$

$$P_\Lambda(k) \equiv |\delta_M(k)|^2 = A\ k\ T^2(k)\, \frac{g^2(\Omega_T^0)}{g^2(\Omega_M^0)}; \quad A = 8.99 \times 10^5 h^{-4}\mathrm{Mpc}^4 \quad (\chi^2 = 0.43)$$

[J. Grande, A. Pelinson, J. Solà, Phys.Rev.D 2009]

Conclusions

- If the dark energy is varying in time...
- The matter density perturbations (as well as the dark energy fluctuations) need to be well defined.
- The growth of the matter density fluctuations (as well as the matter power spectrum) need to be constrained.

Thank you!