Dark degeneracy and observational tests of interacting models

S. Carneiro[1], H. A. Borges[2], C. Pigozzo[3]

[1]Universidade Federal da Bahia/J-PAS
[2]ICG, University of Portsmouth
[3]Imperial College

VI Challenges, Campos do Jordão, 2015

Dark degeneracy

Let us define the dark fluid $$p = \omega\rho$$

and split it as
$$\rho = \rho_m + \Lambda$$
$$p = p_\Lambda = -\Lambda$$

It follows that $$\rho_m = -\frac{\omega+1}{\omega}\Lambda$$

and $$-1 \leq \omega < 0 \;\Rightarrow\; \rho_m \geq 0$$

Zimdahl et al, PRD 64 (2001) 063501
Rubano and Scudellaro, GRG 34 (2002) 1931
Wasserman, PRD 66 (2002) 123511
Kunz, PRD 80 (2009) 123001

Matter creation

Consider Friedmann's equations

$$3H^2 = \rho$$

$$\dot{\rho} + 3H(\rho + p) = 0$$

By using

$$\rho = \rho_m + \Lambda, \qquad p = -\Lambda$$

we have

$$\dot{\rho}_m + 3H\rho_m = -\dot{\Lambda} \quad \Rightarrow \quad \dot{\rho}_m + 3H\rho_m = \Gamma\rho_m \quad \Rightarrow \quad \frac{1}{a^3}\frac{d}{dt}(a^3 n) = \Gamma n$$

where

$$\Gamma = \frac{\dot{\omega}}{1+\omega} - 3\omega H$$

Breaking degeneracy

The conservation equations are

$$T^{\mu\nu}_{m;\nu} = Q^{\mu}$$

$$T^{\mu\nu}_{\Lambda;\nu} = -Q^{\mu}$$

where we define

$$Q^{\mu} = Qu^{\mu} + \bar{Q}^{\mu} \qquad \left(u_{\mu}\bar{Q}^{\mu} = 0\right)$$

For DE we have

$$T^{\mu\nu}_{\Lambda} = \Lambda g^{\mu\nu} \Rightarrow \begin{array}{l} Q = -\Lambda_{,\nu}u^{\nu} \\ \bar{Q}^{\mu} = \Lambda_{,\nu}\left(u^{\mu}u^{\nu} - g^{\mu\nu}\right) \end{array}$$

Linear perturbations give

$$\delta\bar{Q}^{0} = 0$$

$$\delta\bar{Q}_{i} = \left(\delta\Lambda + \dot{\Lambda}\theta\right)_{,i} \equiv \delta\Lambda^{c}_{,i}$$

Hence, $\bar{Q}^{\mu} = 0 \Rightarrow \delta\Lambda^{c} = 0$

Carneiro and Borges, JCAP 1406 (2014) 010
Wands, De-Santiago and Wang, CQG 29 (2012) 145017
Koyama, Maartens and Song, JCAP 0910 (2009) 017

Non-adiabaticity

From the perturbed Einstein equations for a perfect fluid we have

$$\Phi_B'' + 3H(1+c_a^2)\Phi_B' + \left[2H' + (1+3c_a^2)H^2 + c_s^2 k^2\right]\Phi_B = 0$$

$$k^2\Phi_B = -\frac{a^2}{2}\delta\rho^c$$

where Φ_B is the Bardeen gravitational potential, and

$$c_a^2 = \frac{p'}{\rho'}\ , \qquad c_s^2 = \frac{\delta p^c}{\delta\rho^c}$$

The split fluid has $c_s = 0$ and non-adiabatic perturbations:

$$\delta\rho^c = \delta\rho_\Lambda^c + \delta\rho_m^c$$

$$\delta p^c = \delta p_\Lambda^c = -\delta\rho_\Lambda^c$$

$$\Rightarrow \quad \delta p^c - \delta p_{ad}^c = \frac{\rho_\Lambda' \rho_m'}{\rho'}\left(\frac{\delta\rho_m^c}{\rho_m'} - \frac{\delta\rho_\Lambda^c}{\rho_\Lambda'}\right)$$

Hence we can take the following conclusions

Consider a dark fluid with EoS parameter $-1 \leq \omega < 0$. Split it into pressureless DM and DE with EoS parameter $\omega_\Lambda = -1$.

. DM and DE interact and the dark fluid is non-adiabatic.

. DE does not cluster and DM coincides with clustering matter.

. There are no oscillations or instabilities in the power spectrum.

. If we assume DM conservation, the ΛCDM model remains.

Carneiro and Borges, JCAP 1406 (2014) 010

Observational tests

The interaction will be defined by

$$\Lambda = \Lambda_0 \left(\frac{H}{H_0} \right)^{-2\alpha} \quad \Rightarrow \quad \Gamma = -\alpha A H^{-(2\alpha+1)}$$

from which we obtain

$$\rho = 3H_0^2 \left[1 - \Omega_{m0} + \frac{\Omega_{m0}}{a^{3(1+\alpha)}} \right]^{\frac{1}{1+\alpha}}$$

Borges, Carneiro, Fabris and Zimdahl, PLB 727 (2013) 37

For high redshifts,

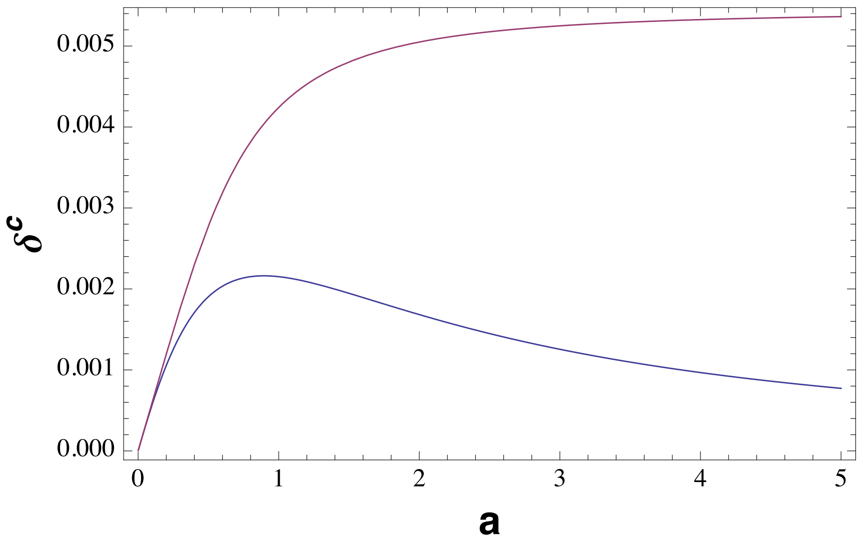
$$\rho_m = 3H_0^2\Omega_{m0}^{1/1+\alpha}z^3 \qquad \qquad (z >> 1)$$

Hence, at matter-radiation equality and last scattering we have, respectively

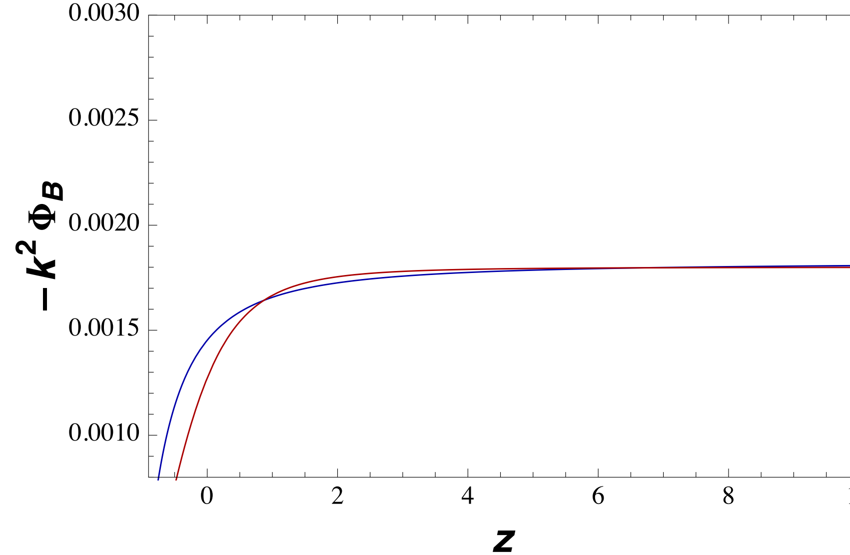
$$z_{eq} = \frac{\Omega_{m0}^{1/1+\alpha}}{\Omega_{R0}} \quad \Rightarrow \quad k_{eq} = 0.073Mpc^{-1}h^2\Omega_{m0}^{1/1+\alpha}$$

$$r_{ls} \equiv \frac{\rho_R}{\rho_m} = \frac{\Omega_{R0}}{\Omega_{m0}^{1/1+\alpha}}z_{ls} \quad \Rightarrow \quad \begin{cases} \delta_1 = 0.267\left(\dfrac{r_{ls}}{0.3}\right)^{0.1} \\ l_1 = l_A(1-\delta_1) \end{cases}$$

These relations are needed when we test LSS and CMB.

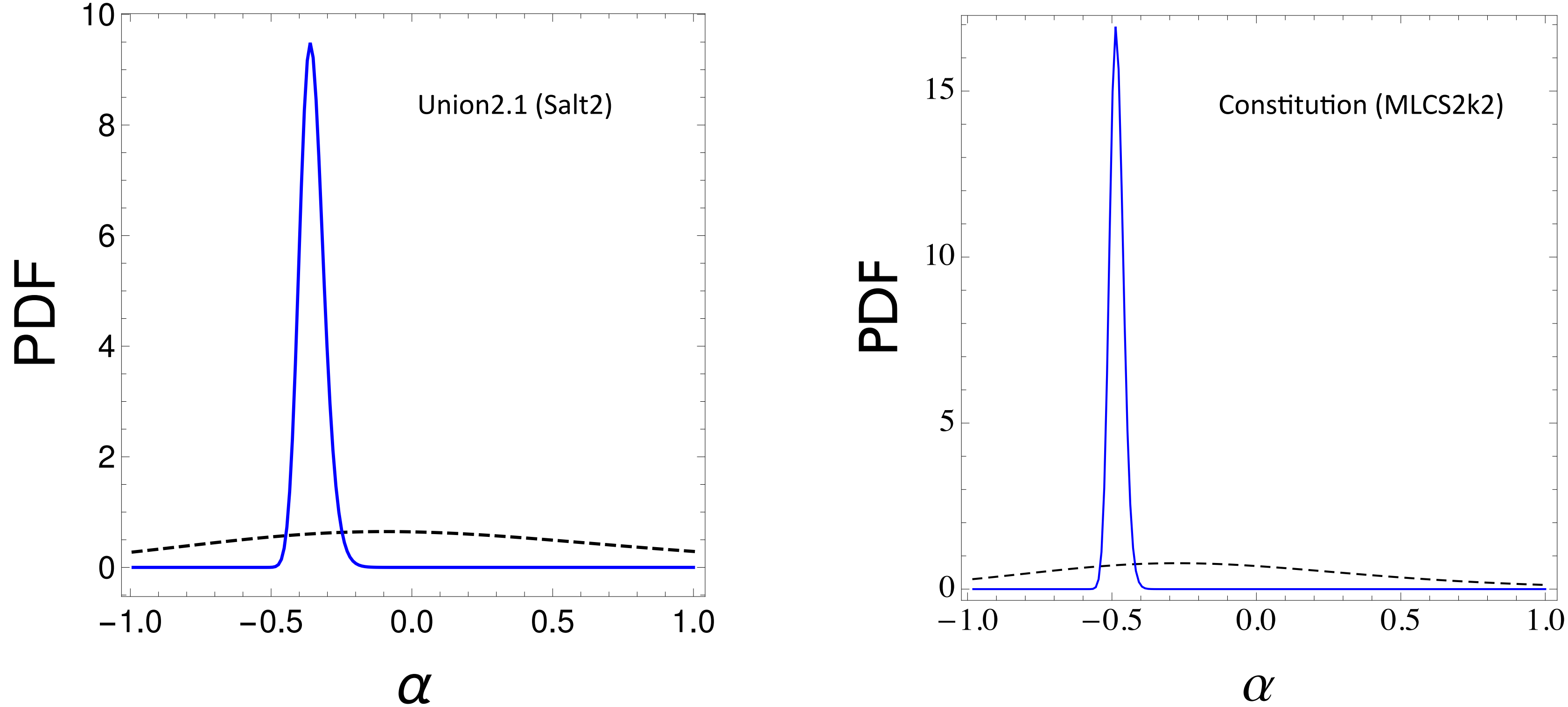


DM and baryonic contrasts for α = −1/2.



Gravitational potential for α = −1/2 and α = 0.

Velten, Borges, Carneiro, Fazolo and Gomes, arXiv:1504.02416



Joint analyses of Sne Ia + LSS + CMB. The dotted lines are PDFs for supernovae only.

Carneiro and Pigozzo, JCAP 1410 (2014) 060

Further references

Alcaniz, Borges, Carneiro, Fabris, Pigozzo and Zimdahl, PLB 716 (2012) 165

Pigozzo, Dantas, Carneiro and Alcaniz, JCAP 1108 (2011) 022

Zimdahl, Borges, Carneiro, Fabris and Hipólito-Ricaldi, JCAP 1104 (2011) 028

Borges, Carneiro, Fabris and Pigozzo, PRD **77** (2008) 043513

Chandrachani Dev, Borges, Carneiro and Alcaniz, MNRAS 448 (2015) 37

vom Marttens, Hipólito-Ricaldi and Zimdahl, JCAP 1408 (2014) 004

Velten, Montiel and Carneiro, MNRAS 431 (2013) 3301