Dark degeneracy and interacting models

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Dark degeneracy

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

and split it as

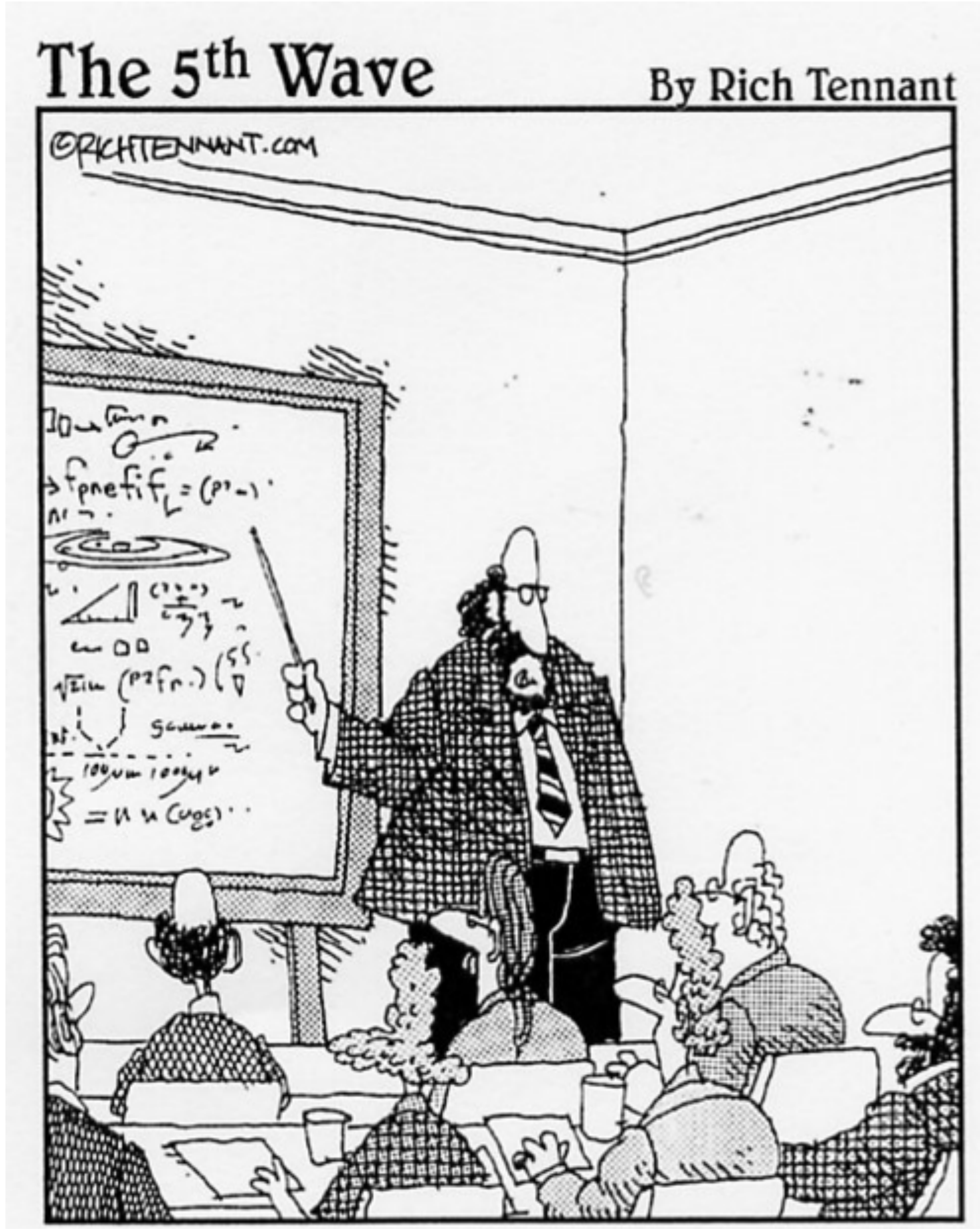
$$\rho = \rho_m + \Lambda$$
$$p = p_\Lambda = -\Lambda$$

It follows that

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

and $-1 \leq \omega < 0$ ⇒ $\rho_m \geq 0$

Kunz, PRD 80 (2009) 123001
Wasserman, PRD 66 (2002) 123511
Rubano and Scudellaro, GRG 34 (2002) 1931



"After the discovery of 'antimatter' and 'dark matter', we have just confirmed the existence of 'doesn't matter', which does not have any influence on the Universe whatsoever."

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

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

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

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

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,

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

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

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

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

$$\delta\rho^c = \delta\rho^c_\Lambda + \delta\rho^c_m$$
$$\delta p^c = \delta p^c_\Lambda = -\delta\rho^c_\Lambda$$

$$\Rightarrow \quad \delta p^c - \delta p^c_{ad} = \frac{\rho'_\Lambda \rho'_m}{\rho'}\left(\frac{\delta\rho^c_m}{\rho'_m} - \frac{\delta\rho^c_\Lambda}{\rho'_\Lambda}\right)$$

Theorem

Let it be a dark fluid with EoS parameter $-1 \leq \omega < 0$. Let us split this fluid into pressureless DM and DE with EoS parameter $\omega_{\Lambda} = -1$.

. DM is created with rate Γ and the dark fluid is non-adiabatic.

. If there is negligible momentum transfer, DE does not cluster and DM coincides with clustering matter.

. In this case, there are no oscillations or instabilities in the power spectrum.

Corollaries

. An observational analysis which identifies pressureless matter with clustering matter leads to $\omega \approx -1$.

. If, in addition, such an analysis assumes that clustering matter is conserved, the best concordance is given by the ΛCDM model.

Chaplygin gas

The gas is defined by $$p = -\frac{A}{\rho^{\alpha}} \quad \Rightarrow \quad \rho = \left[A + \frac{B}{a^{3(1+\alpha)}}\right]^{\frac{1}{1+\alpha}}$$

From the split $$\rho = \rho_m + \Lambda \,, \qquad p = p_\Lambda = -\Lambda$$

we have $$\Lambda = \Lambda_0 \left(\frac{H}{H_0}\right)^{-2\alpha} \quad \Rightarrow \quad \Gamma = -\frac{\alpha A}{3^{\alpha}} H^{-(2\alpha+1)}$$

Borges, Carneiro, Fabris and Zimdahl, PLB 727 (2013) 37.
Wang, Wands, Xu, De-Santiago and Hojjati, PRD **87** (2013) 083503.
Reis, Waga, Calvao and Joras, PRD **68** (2003) 061302.

Observational tests

For high redshifts,

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

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

$$z_{eq} = \frac{\Omega_{m0}^{1/1+\alpha}}{\Omega_{R0}} \qquad r_{ls} \equiv \frac{\rho_R}{\rho_m} = \frac{\Omega_{R0}}{\Omega_{m0}^{1/1+\alpha}} z_{ls}$$

These relations are implicitly used when we test LSS and CMB!

Constant-rate creation

$$\alpha = -1/2 \quad \Rightarrow \quad \rho_\Lambda = 2\Gamma H = \frac{2}{3}\Gamma\Theta \qquad \left(\Theta = u^\mu_{;\mu}\right)$$

Perturbations give

$$\frac{\delta\rho^c_\Lambda}{\rho_\Lambda} = -\frac{1}{K}\left(a\frac{\partial\delta^c_m}{\partial a} + B\delta^c_m\right) \qquad \left(\delta^c_m = \frac{\delta\rho^c_m}{\rho_m}\right)$$

For observed scales,

$$\frac{k}{Ha} >> 1 \quad \Rightarrow \quad K >> 1 \quad \Rightarrow \quad \delta\rho^c_\Lambda << \delta\rho^c_m$$

Borges and Carneiro, GRG 37 (2005) 1385

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

Concordance

TABLE I: Limits to Ω_{m0} (SNe Ia + CMB + BAO + LSS), for $\alpha = -1/2$ [3].

	Chaplygin gas		ΛCDM	
SNe Ia sample	$\Omega_{m0}{}^a$	χ^2_{min}/ν	$\Omega_{m0}{}^a$	χ^2_{min}/ν
Union2 (SALT2)......	$0.420^{+0.009}_{-0.010}$	1.063	0.235 ± 0.011	1.027
SDSS (MLCS2k2).......	$0.450^{+0.014}_{-0.010}$	0.842	$0.260^{+0.013}_{-0.016}$	1.231
Constitution (MLCS2k2-17).......	$0.450^{+0.008}_{-0.014}$	1.057	0.270 ± 0.013	1.384

$$t_0 \approx 13.5 Gyr$$

Borges, Carneiro, Fabris and Pigozzo, PRD **77** (2008) 043513
Pigozzo, Dantas, Carneiro and Alcaniz, JCAP **1108** (2011) 022
Alcaniz, Borges, Carneiro, Fabris, Pigozzo and Zimdahl, PLB 716 (2012) 165
Velten, Montiel and Carneiro, MNRAS 431 (2013) 3301
vom Marttens, Hipólito-Ricaldi and Zimdahl, arXiv:1403.0427

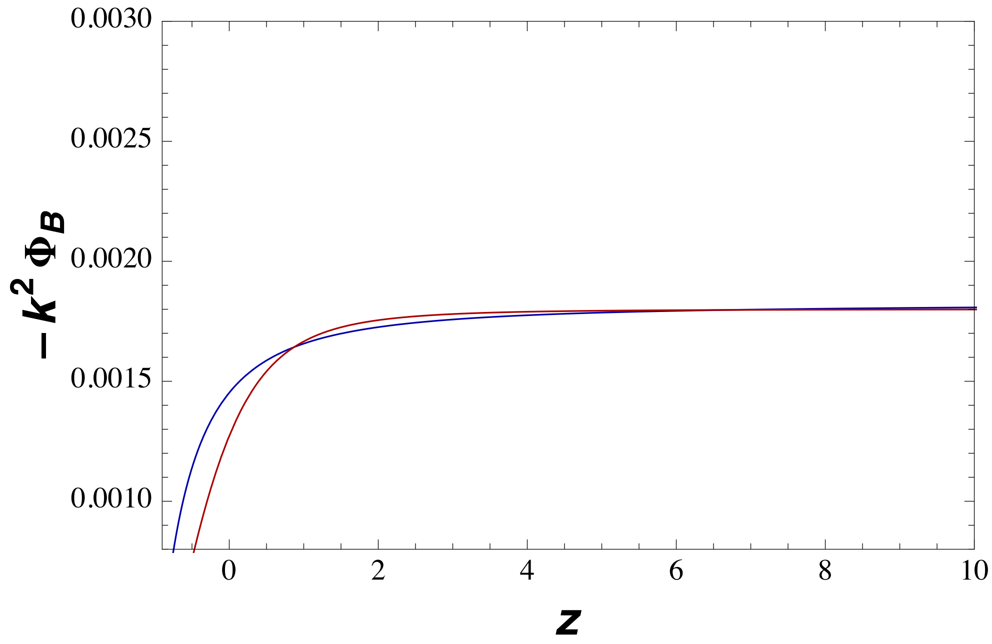
CMB

Same pre-recombination physics as in SM

Standard radiation and baryonic contents

Same DM density at high redshifts

Almost the same SW and ISW



Obrigado!