PHYSICAL REVIEW D **74,** 063524 (2006)

Is it possible to observationally distinguish adiabatic quartessence from ΛCDM?

L. Amendola,[1] M. Makler,[2] R. R. R. Reis,[3] and I. Waga[3]

[1]*INAF/Osservatorio Astronomico di Roma, Via Frascati 33, I-00040 Monte Porzio Catone, RM, Italy*
[2]*Centro Brasileiro de Pesquisas Físicas, CEP 22290-180, Rio de Janeiro, RJ, Brazil*
[3]*Universidade Federal do Rio de Janeiro, Instituto de Física, CEP 21941-972, Rio de Janeiro, RJ, Brazil*

(Received 2 April 2006; published 27 September 2006)

The equation of state (EOS) in quartessence models interpolates between two stages: $p \simeq 0$ at high energy densities and $p \approx -\rho$ at small ones. In the quartessence models analyzed up to now, the EOS is convex, implying increasing adiabatic sound speed (c_s^2) as the energy density decreases in an expanding universe. A nonnegligible c_s^2 at recent times is the source of the matter power spectrum problem that plagued all convex (nonsilent) quartessence models. Viability for these cosmologies is only possible in the limit of almost perfect mimicry to ΛCDM. In this work we investigate if similarity to ΛCDM is also required in the class of quartessence models whose EOS changes concavity as the Universe evolves. We focus our analysis in the simple case in which the EOS has a steplike shape, such that at very early times $p \simeq 0$, and at late times $p \simeq \text{const} < 0$. For this class of models a nonnegligible c_s^2 is a transient phenomenon and could be relevant only at a more early epoch. We show that agreement with a large set of cosmological data requires that the transition between these two asymptotic states would have occurred at high redshift ($z_t \gtrsim 38$). This leads us to conjecture that the cosmic expansion history of any successful nonsilent quartessence is (practically) identical to the ΛCDM one.

DOI: 10.1103/PhysRevD.74.063524 PACS numbers: 95.35.+d, 98.80.Cq

I. INTRODUCTION

In the current standard cosmological model, two unknown components govern the dynamics of the Universe: dark matter (DM), responsible for structure formation, and dark energy (DE), that drives cosmic acceleration. Recently, an alternative point of view has started to attract considerable interest. According to it, DM and DE are simply different manifestations of a single unifying dark-matter/energy (UDM) component. Since it is assumed that there is only one dark component in the Universe, besides ordinary matter, photons and neutrinos, UDM is also referred to as quartessence [1].

A prototype candidate for such unification is the quartessence Chaplygin model (QCM) [2]. Although this model is compatible with the background data [3], problems appear when one considers (adiabatic) perturbations. For instance, the CMB anisotropy is strongly suppressed when compared with the ΛCDM model [4]. Further, it was shown that the matter power spectrum presents oscillations and instabilities that reduce the parameter space of the model to a region very close to the ΛCDM limit [5]. However, these oscillations and instabilities in the matter power spectrum and the CMB constraints can be circumvented by assuming silent perturbations [6,7], i.e., intrinsic entropy perturbations with a specific initial condition ($\delta p = 0$). In fact, silent perturbations solve the matter power spectrum problem for more generic quartessence [8]. Efforts to solve the matter power spectrum problem also have been put forward in [9,10]. However, we understand that these works are not, strictly speaking, quartessence. In fact, [9] introduces what seems to be a particular splitting of the Chaplygin model. It is a two component system although only one component is perturbed. A way to implement silent perturbations is presented in [10], but they use additional fields that can be interpreted as new matter components.

In this work we present a possible alternative to solve the above mentioned problems in the context of the more standard adiabatic perturbations scenario. We shall discuss a model in which the quartessence EOS changed its concavity in some instant in the past. We focus our investigation on models with a steplike shape EOS. We show that, in order to be in accordance with observations, the EOS concavity change would have occurred at high redshifts. Similarly to what happens in the Chaplygin case, observations constrain one of the parameters of the model to such a low value that, at least at zero and first orders, the steplike model cannot be observationally distinguished from the ΛCDM model.

II. A NEW TYPE OF QUARTESSENCE

In the quartessence models explicitly analyzed up to now, the EOS is convex, i.e., is such that

$$\frac{d^2 p}{d\rho^2} = \frac{dc_s^2}{d\rho} < 0. \tag{1}$$

Stability for adiabatic perturbations and adiabatic sound speed less than c imply

$$0 \le c_s^2 \le 1. \tag{2}$$

Condition (2) and the fact that $p < 0$ immediately implies the existence of a minimum energy density $\rho_{\min}$, once the energy conservation equation is used. This is a generic result for any uncoupled fluid model in which $w = w(\rho)$.

 © 2006 The American Physical Society

It implies that the $p = -\rho$ line cannot be crossed and that in any such a quartessence model the minimum value of the EOS parameter is $w_{\min} = -1$. The convexity condition (1) implies that $c_{s\,\max}^2$ occurs at $\rho = \rho_{\min}$. This last result is only a consequence of the convexity of the EOS. In this case, the epoch of accelerated expansion is also a period of high adiabatic sound speed, causing the oscillations and suppressions in the power spectrum. However, this property is not mandatory for quartessence. Models with concavity changing equations of state may have c_s^2 negligibly small at $\rho \simeq \rho_{\min}$. As we shall show, it is possible to build models in which a nonnegligible c_s^2 is a transient phenomenon and relevant only at a very early epoch, such that only perturbations with relatively large wave numbers (outside the range of current linear power spectrum measurements) are affected.

The steplike quartessence, given by a sigmoid, is an example of UDM with concavity changing EOS (see Fig. 1, left panel),

$$p = -M^4\left\{\frac{1}{1 + \exp[\beta(\frac{\rho}{M^4} - \frac{1}{\sigma})]}\right\}. \tag{3}$$

For this model, the adiabatic sound speed has the following expression:

$$c_s^2 = \beta\frac{\exp[\beta(\frac{\rho}{M^4} - \frac{1}{\sigma})]}{\{1 + \exp[\beta(\frac{\rho}{M^4} - \frac{1}{\sigma})]\}^2}. \tag{4}$$

There are three free parameters in the model. The parameter M is related to the minimum value of the energy density, i.e., the value of ρ when the asymptotic EOS, $p_{\min} = -\rho_{\min}$, is reached. The parameter σ is related to the value of the energy density at the transition from the $p \simeq 0$ regime to the $p \simeq -M^4$ one ($\rho_{\rm trans} = M^4/\sigma$). Notice that if $\sigma \ll 1$, the transition takes place well before the minimum density is reached. The parameter β controls the maximum sound velocity $c_{s\,\max}^2$ as well as the redshift width of the transition region (higher values of β implying faster transitions). For the sigmoid EOS the maximum adiabatic sound speed is given by $c_{s\,\max}^2 = \beta/4$, and therefore we require $0 \leq \beta \leq 4$.

In the present model, the ΛCDM limit is not necessarily associated with the maximum sound speed, in contrast to what is found in the convex EOS case. The ΛCDM limit is reached when $\sigma \to 0$, which implies $p = -\rho = -M^4$. Another possibility is to take $\beta \to 0$. In this case $c_{s\,\max}^2 \to 0$ and we also have a ΛCDM limit, but now with $p = -\rho = -M^4/2$. Since β strongly affects the redshift width of the transition, these two limits have different characteristics. The case of a nonvanishing $\beta \ll 1$ has a drastic effect on the matter power spectrum. In fact, although the maximum sound speed will be small, it will be nonnegligible during a long redshift range and/or time, practically ruling out these models.

We note that a steplike quartessence may be represented by the more generic expression,

$$p = M^4 f\left[\beta\left(\frac{\rho}{M^4} - \frac{1}{\sigma}\right)\right], \tag{5}$$

where f is a steplike function, with $f(+\infty) = 0$ and $f(-\infty) = -1$. The maximum adiabatic sound speed is $c_{s\,\max}^2 = \beta f'_{\max}$. For $\sigma \ll 1$, $p_{\min} = -M^4$.

III. OBSERVATIONAL CONSTRAINTS

The zeroth order quantities (such as the luminosity and angular diameter distances), depend only on integrals of the Hubble parameter. Therefore, they are not very sensitive to local features of the function $\rho(a)$. In particular,

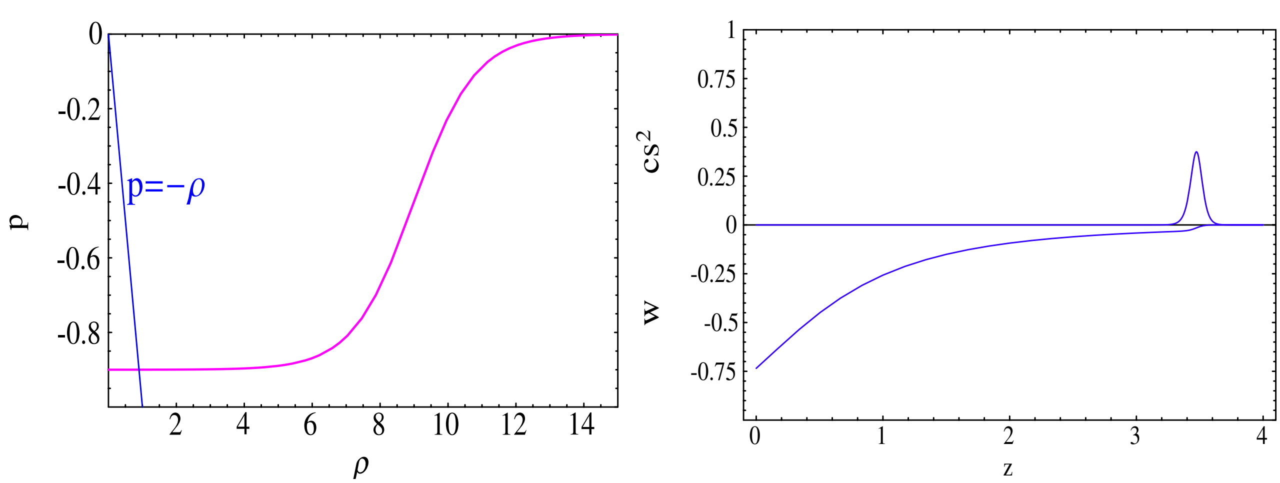

FIG. 1 (color online). Left panel: pressure (p) as a function of the energy density (ρ) for the sigmoid EOS. Also shown is the $p = -\rho$ line. Right panel: typical behavior of the EOS parameter (w) and the adiabatic sound speed (c_s^2) as a function of the redshift (z).

they should not depend on the specific form of the transition from $p = 0$ to $p = -M^4$. For example, for small values of σ, the observational data (from SNIa, for instance) constrains only M^4 and not σ nor β. Thus we expect the background observational constraints to be highly degenerate for small σ ($\sigma \lesssim 0.1$). Further, as will be shown, first order tests, such as cosmic microwave background fluctuations or large-scale structure data, constrain the value of σ to be very small ($\sigma \ll 1$). Therefore, a real step function is a good model-independent approximation for the background evolution in the type of quartessence we are dealing with in this paper.

In the following we derive constraints on the parameters σ and M^4/ρ_0 from four data sets: SNIa, x-ray cluster gas mass fraction, galaxy power spectrum and CMB fluctuations. Here, ρ_0 is the present value of the quartessence energy density. For the sake of simplicity, in our computations we fixed the parameter β to the intermediary value $\beta = 2$. We remark that, for small values of σ, $-M^4/\rho_0 \simeq w_0$, where w_0 is the present equation of state parameter. It is worth pointing out that w_0 should not be compared to the usual dark energy EOS $w_{\rm DE}$ but with $w_{\rm eff} \equiv w_{\rm tot}\Omega_{\rm tot}$. In a flat universe and neglecting the small amount of baryons $w_{\rm eff} \equiv w_{\rm DE}\Omega_{\rm DE}$. Values around $M^4/\rho_0 \approx 0.7$ are therefore to be expected.

In our SNIa analysis we use the "gold" data set of Riess *et al.* [11]. To determine the likelihood of the parameters we follow the same procedure described in [7] assuming

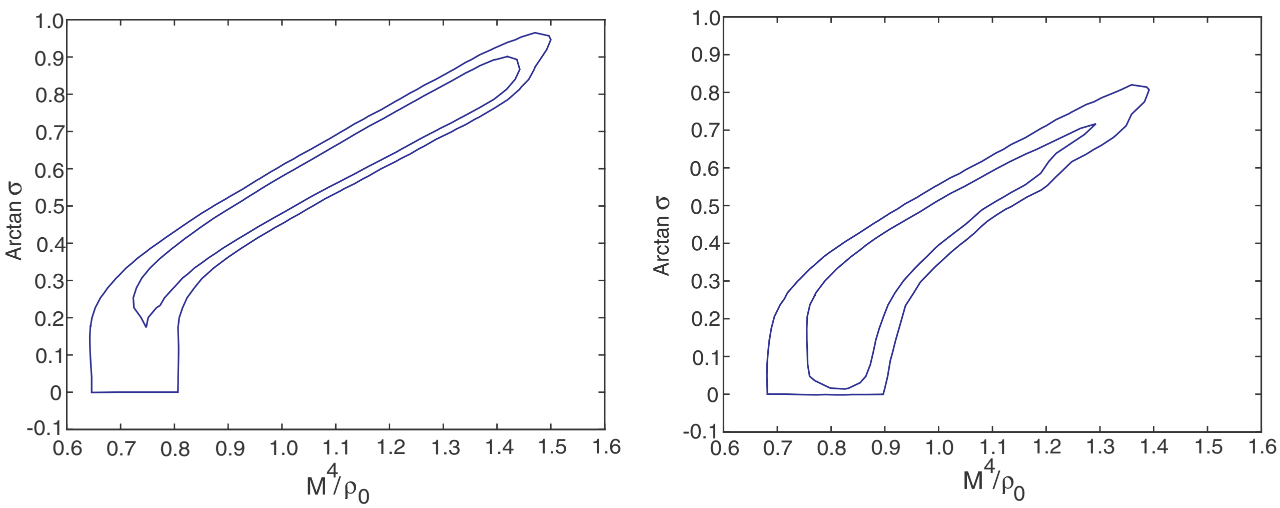

FIG. 2 (color online). Constant confidence contours (68% and 95%) in the (M^4/ρ_0, arctanσ) plane allowed by SNeIa (left panel) and X-ray galaxy clusters (right panel).

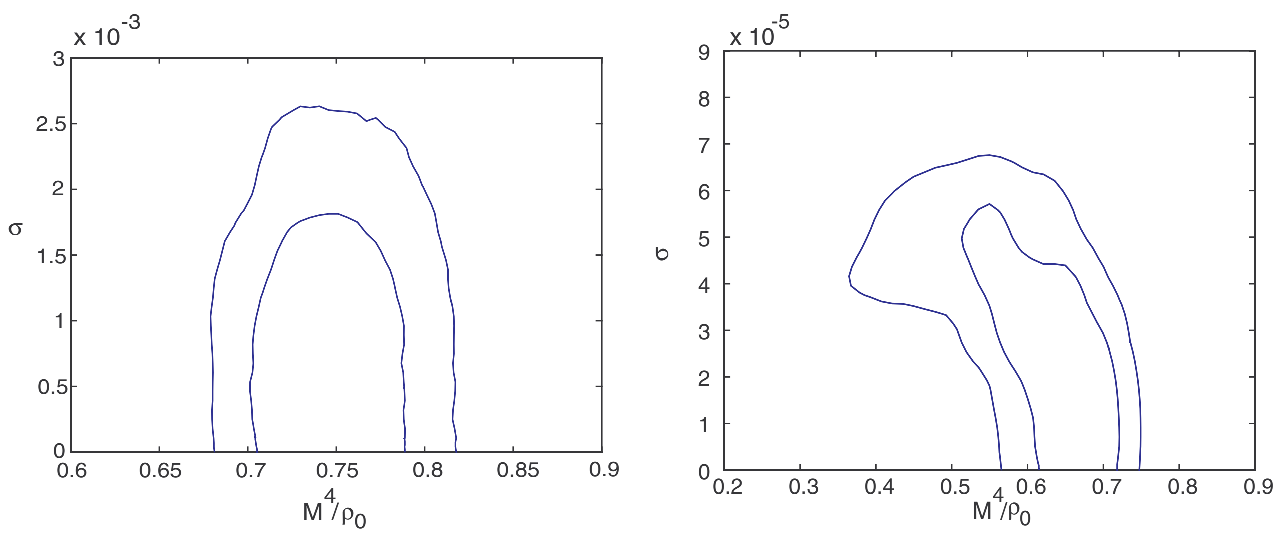

FIG. 3 (color online). Constant confidence contours (68% and 95%) in the (M^4/ρ_0, σ) plane allowed by CMB (WMAP) [13] (left panel) and matter power spectrum (SDSS) [14] (right panel).

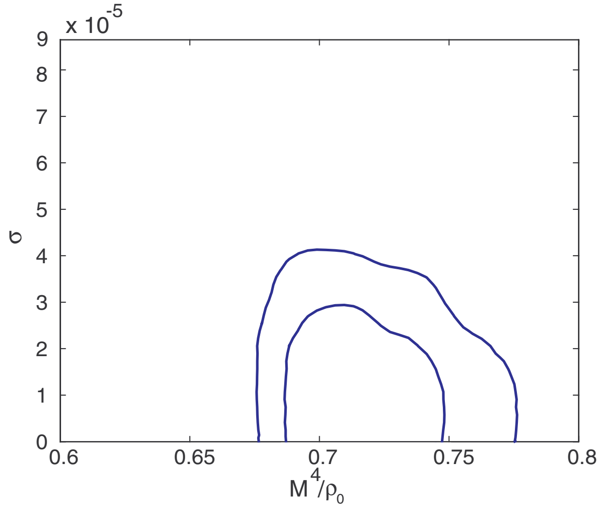

FIG. 4 (color online). 68% and 95% in the $(M^4/\rho_0, \sigma)$ plane for the combined analysis SNIa + galaxy clusters + matter power spectrum + CMB.

flat priors when marginalizing over the baryon density parameter $\Omega_{b0}h^2$ and Hubble parameter h. For the galaxy cluster analysis, we use the *Chandra* measurements of the x-ray gas mass fraction data from Allen *et al.* [12]. Again, we follow the same procedure described in [7] to determine confidence region of the parameters of the model. We first marginalize analytically over the bias b, using a Gaussian prior with $b = 0.824 \pm 0.089$ and then, as in the SNIa analysis, we marginalize over $\Omega_{b0}h^2$ and h assuming flat priors. In Fig. 2 we show constant 68% and 95% confidence levels contours on the parameters M^4/ρ_0 and σ for SNIa and x-ray galaxy clusters. From the figure it is clear that, as expected, background tests impose only weak constraints on the parameter σ.

In order to obtain constraints on M^4/ρ_0 and σ from CMB data [13] we follow the procedure described in [7], fixing $T_{\rm CMB} = 2.726$ K, $Y_{\rm He} = 0.24$, and $N_\nu = 3.04$, and marginalizing over the other parameters, namely, $\Omega_{b0}h^2$, h, the spectral index n_s, the optical depth τ, and the normalization N. In Fig. 3 (left panel) we show the confidence region on the parameters for CMB. Note that σ plays a decisive role in the evolution of perturbations; now the data constrain this parameter to be $\sigma \lesssim 3 \times 10^{-3}$.

We next consider the matter power spectrum, comparing the baryon spectrum with data from SDSS [14]. To compute the likelihood, we used a version of the code provided by M. Tegmark [15], cutting at $k = 0.20\ h\,{\rm Mpc}^{-1}$ (19 bands) and marginalizing over $\Omega_{b0}h^2$, h, n_s and the amplitude. In Fig. 3 (right panel) we show the 68% and 95% confidence levels on σ and M^4/ρ_0 from the SDSS power spectrum. This is the most restrictive test we have considered in this work, implying that $\sigma \lesssim 7 \times 10^{-5}$.

In Fig. 4 we display the constant (68% and 95%) contours for the combined analysis SNIa + x ray galaxy clusters + matter power spectrum + CMB data. Our final result (95%) is $0.68 \lesssim M^4/\rho_0 \lesssim 0.78$ and $0 < \sigma \lesssim 4 \times 10^{-5}$. It is straightforward to show that the transition redshift from a pressureless epoch to a constant negative pressure period is given by $z_t \simeq [(M^4/\rho_0) \times (1-\sigma)/((1-M^4/\rho_0)\sigma)]^{1/3}$. Therefore, assuming $M^4/\rho_0 \sim 0.7$ and since $\sigma \lesssim 4 \times 10^{-5}$ the transition from $p = 0$ to $p = -M^4$ would have occurred at $z_t \gtrsim 38$.

IV. CONCLUSION

In this work we presented a new adiabatic quartessence model characterized by a change of concavity in the EOS. We obtained the constraints on the model parameters from SNIa, x-ray gas mass fraction in galaxy clusters, CMB, and matter power spectra and showed that the model is viable if $\sigma \lesssim 4 \times 10^{-5}$. The redshift of the transition from the regime $p \simeq 0$ to $p \simeq$ const. < 0 is, therefore, $z_t \gtrsim 38$. On the other hand, the inclusion of matter power spectrum data for smaller scales ($k \gtrsim 0.2\ h\,{\rm Mpc}^{-1}$) could impose stronger constraints upon σ pushing the minimum redshift of the transition to higher values. We checked that this is, in fact, the case by considering data from the matter power spectrum from the Lyman-alpha forest [16]. However, since there are still systematic uncertainties in this data, we did not include them in our analysis. Although differences between quartessence models and ΛCDM may exist in the nonlinear regime [17], the results of the present work, in combination with the results of [5,7], indicate that at zero and first orders, any (convex or not) successful adiabatic quartessence model cannot be observationally distinguished from ΛCDM.

ACKNOWLEDGMENTS

We thank Roberto Colistete and Miguel Quartin for useful discussions. The CMB computations have been performed at CINECA (Italy) under the agreement INAF@CINECA. We thank the staff for support. R. R. R. R. and I. W. are partially supported by the Brazilian research agencies CAPES and CNPq, respectively. L. A. thanks the Gunma Nat. Coll. of Techn. (Japan) for hospitality during the later stages of this work and JSPS for financial support.

[1] M. Makler, S. Q. Oliveira, and I. Waga, Phys. Lett. B **555**, 1 (2003).

[2] A. Kamenshchik, U. Moschella, and V. Pasquier, Phys. Lett. B **511**, 265 (2001); M. Makler, Ph.D. thesis, Brazilian Center for Research in Physics, 2001; N. Bilić, G. B. Tupper, and R. D. Viollier, Phys. Lett. B **535**, 17 (2002); M. C. Bento, O. Bertolami, and A. A. Sen, Phys. Rev. D **66**, 043507 (2002).

[3] M. Makler, S. Q. Oliveira, and I. Waga, Phys. Rev. D **68**, 123521 (2003); A. Dev, D. Jain, and J. S. Alcaniz, Astron. Astrophys. **417**, 847 (2004); Z.-H. Zhu, Astron. Astrophys. **423**, 421 (2004); R. Colistete, Jr. and J. C. Fabris, Classical Quantum Gravity **22**, 2813 (2005); M. C. Bento, O. Bertolami, N. M. C. Santos, and A. A. Sen, Phys. Rev. D **71**, 063501 (2005).

[4] D. Carturan and F. Finelli, Phys. Rev. D **68**, 103501 (2003); L. Amendola, F. Finelli, C. Burigana, and D. Carturan, J. Cosmol. Astropart. Phys. 07 (2003) 005.

[5] H. B. Sandvik, M. Tegmark, M. Zaldarriaga, and I. Waga, Phys. Rev. D **69**, 123524 (2004).

[6] R. R. R. Reis, I. Waga, M. O. Calvão, and S. E. Jorás, Phys. Rev. D **68**, 061302(R) (2003).

[7] L. Amendola, I. Waga, and F. Finelli, J. Cosmol. Astropart. Phys. 11 (2005) 009.

[8] R. R. R. Reis, M. Makler, and I. Waga, Classical Quantum Gravity **22**, 353 (2005).

[9] M. C. Bento, O. Bertolami, and A. A. Sen, Phys. Rev. D **70**, 083519 (2004).

[10] N. Bilic, G. B. Tupper, and R. D. Viollier, hep-th/0504082.

[11] A. G. Riess *et al.*, Astrophys. J. **607**, 665 (2004).

[12] S. W. Allen *et al.*, Mon. Not. R. Astron. Soc. **353**, 457 (2004).

[13] G. Hinshaw *et al.* (WMAP Collaboration), Astrophys. J. Suppl. Ser. **148**, 135 (2003); L. Verde *et al.* (WMAP Collaboration), Astrophys. J. Suppl. Ser. **148**, 195 (2003).

[14] M. Tegmark *et al.* (SDSS Collaboration), Phys. Rev. D **69**, 103501 (2004); Astrophys. J. **606**, 702 (2004).

[15] M. Tegmark, http://space.mit.edu/home/tegmark/sdss.html.

[16] R. A. C. Croft *et al.*, Astrophys. J. **520**, 1 (1999); N. Y. Gnedin and A. J. S. Hamilton, Mon. Not. R. Astron. Soc. **334**, 107 (2002).

[17] D. Giannakis and W. Hu, Phys. Rev. D **72**, 063502 (2005).