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An alternative to the cosmological ‘concordance model’

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Abstract. Precision measurements of the cosmic microwave background by WMAP are believed to have established a flat Λ -dominated universe, seeded by nearly scale-invariant adiabatic primordial fluctuations. However by relaxing the hypothesis that the fluctuation spectrum can be described by a single power law, we demonstrate that an Einstein-de Sitter universe with *zero* cosmological constant can fit the data as well as the best concordance model. Moreover unlike a Λ -dominated universe, such an universe has no strong integrated Sachs-Wolfe effect, so is in better agreement with the low quadrupole seen by WMAP. The main problem is that the Hubble constant is required to be rather low: $H_0 \simeq 46$ km/s/Mpc; we discuss whether this can be consistent with observations. Furthermore for universes consisting only of baryons and cold dark matter, the amplitude of matter fluctuations on cluster scales is too high, a problem which seems generic. However, an additional small contribution ($\Omega_X \sim 0.1$) of matter which does not cluster on small scales, e.g. relic neutrinos with mass of order eV or a ‘quintessence’ with $w = 0$, can alleviate this problem. Such models provide a satisfying description of the power spectrum derived from the 2dF galaxy redshift survey and from observations of the Ly- α forest. We conclude that Einstein-de Sitter models can indeed accommodate all data on the large scale structure of the Universe, hence the Hubble diagram of distant Type Ia supernovae remains the only *direct* evidence for a non-zero cosmological constant.

Key words. Cosmology – Cosmic microwave background – Large scale structure – Cosmological parameters

1. Introduction

Measurements of cosmological parameters with reasonable accuracy are essential both to establish a robust picture of the standard Big Bang cosmology, and to provide insights into the fundamental processes far beyond the Standard Model of particle physics which determined its initial conditions. Since the pioneering work of Hubble, it has been recognised that cosmological tests based on astrophysical arguments can suffer from large systematic biases. It can therefore be argued that one should as far as possible use methods which avoid such arguments or, more generally, do not depend explicitly on assumptions concerning complex astrophysical phenomena.

In this respect, measurements of anisotropies in the Cosmic Microwave Background (CMB) appear to offer the most promise for accurate determination of cosmological parameters, thanks to the high control possible on systematic errors. Since the epochal discovery of primordial fluctuations on large angular scales by COBE (32), this field has witnessed a renaissance. The first detections of fluctuations on degree scales (Netterfield et al. 1995; Scott et al.

1996) provided tantalizing evidence for the flatness of the Universe (e.g. Lineweaver et al. 1997). The unambiguous detection of the first and second acoustic peaks in the angular power spectrum (de Bernardis et al. 2000; Hanany et al. 2000; Halverson et al. 2002) has confirmed this result. Taken together with studies of large-scale structure (LSS) in the universe, these observations have also confirmed the overall picture of structure formation through gravitational instability. The recent results obtained by WMAP represent a further major advance in the field. For the first time, measurements of cosmological parameters are being quoted with $\sim 1\%$ uncertainties, opening up the anticipated era of ‘precision cosmology’. Our intention here is to examine whether such determinations are in fact robust or depend crucially on underlying assumptions. Specifically we wish to test whether a cosmological constant, Λ , is really required by observations of the CMB and LSS. We will do so by confronting Einstein-de Sitter (E-dS) models with the same observations. It turns out that with a different assumption concerning the spectrum of primordial fluctuations generated by inflation, such models fit the data even better than models with non-zero Λ .

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2. What do the C_ℓ measurements imply?

The physics of passive linear perturbations in the early Universe is well understood and therefore their evolution can be computed accurately (see Hu & Dodelson 2002). This is the basic reason why precise measurements of the angular structure of the imprints left on the CMB by primordial fluctuations can provide accurate information on cosmological parameters. The ingredients necessary to compute the amplitudes of the multipole moments (C_ℓ) specifying the angular power spectrum are the nature and spectrum of the primordial fluctuations (presumably arising from inflation), as well as specification of the various contents of the universe which contribute to its density and pressure. The imprint of a specific parameter can be direct, through the influence on the dynamics of acoustic oscillations before the epoch of last scattering (as for the baryonic content of the universe for instance), as well as indirect, through the effect on the angular distance to the last scattering surface. A non-zero Λ affects the C_ℓ s primarily through the distance effect (Blanchard 1984). More subtle effects exist, like the integrated Sachs-Wolf effect, which contribute at a much weaker level. However such effects are much more difficult to identify, as they can also be mimicked by a non-trivial primordial fluctuation spectrum.

The first studies of the generation of density perturbations during inflation established (see Linde 1990) that for the simplest models involving a single ‘inflaton’ field, the spectrum is close to the Harrison-Zel’dovich (H-Z) scale-invariant form, $P(k) \propto k^n$ with $n = 1$, which had been proposed earlier on grounds of simplicity. Thus the H-Z spectrum became a standard input for calculations of CMB anisotropies and the growth of LSS, e.g. in the standard cold dark matter (SCDM) model (Davis et al. 1985). In fact there are significant corrections to a H-Z spectrum even in single-field models, in particular the spectrum steepens logarithmically with increasing k (decreasing scale) as the end of inflation is approached. This is usually accommodated by considering a ‘tilted’ spectrum with $n < 1$, although it should be noted that the index n is scale-dependent for any polynomial potential for the inflaton, and is constant only for an exponential potential (power-law inflation). Moreover n can be very close to, and even exceed, unity if inflation ends not through the steepening of the inflaton potential but, for example, due to the dynamics of a second scalar field (hybrid inflation). In such multi-field models, the spectrum may not even be scale-free since features can be imprinted onto the spectrum when the slow-roll evolution of the inflaton is interrupted by other background fields undergoing symmetry-breaking phase transitions (Adams, Ross & Sarkar 1997b).

The expectations for the spectral index $n(k)$ in various inflationary models has been reviewed by Lyth & Riotto (1999). Even small departures from scale-invariance can be quite significant, for example after the SCDM model was found by Efstathiou et al. (1992) to be in conflict with the observed power spectrum of galaxy clustering

and could not reproduce simultaneously the amplitude of COBE fluctuations and the abundance of rich clusters (quantified by the variance σ_8 in a top-hat sphere of radius $8h^{-1}$ Mpc), it was pointed out by White et al. (1995) that invoking a tilted spectrum with $n \simeq 0.9$ could save the model. Interestingly enough, such a spectrum arises in the natural ¹ supergravity inflation model, where the leading term in the potential is *cubic* in the field (Ross & Sarkar 1996; Adams, Ross & Sarkar 1997a, see Sarkar 1996b). This yields $n = (N-2)/(N+2)$, where $N \lesssim 57 + \ln(k^{-1}/3000h^{-1} \text{ Mpc})$ is the number of e-folds of expansion from the end of inflation, taking the inflationary energy scale to be $\lesssim 10^{16}$ GeV as required by the normalization to COBE, and the reheat temperature to be $\lesssim 10^9$ GeV to avoid the thermal gravitino problem (see Sarkar 1996a). Note that if the inflationary scale is much lower (German, Ross & Sarkar 2001) and/or if there was a late epoch of thermal inflation (Lyth & Stewart 1996), then our present Hubble radius of $H_0^{-1} \simeq 3000h^{-1}$ Mpc may have exited the horizon only $\sim 20-30$ e-folds from the end of inflation, implying a spectral index as low as $n \simeq 0.8$ on cosmologically observable scales since $n \simeq 1 - 4/N$ in this model.

It is thus clear that the primordial spectrum may not have a trivial form and lacking a ‘standard model’ of inflation, it is necessary to consider a wide range of possibilities. Furthermore such complex spectra could potentially confuse cosmological parameter estimation from CMB data (e.g. Kinney 2001). This was explicitly demonstrated by Barriga et al. (2001) using the COBE and BOOMERanG data (de Bernardis et al. 2000) for the case of a primordial spectrum with a ‘step’, as expected in double (Silk & Turner 1987) or multiple (Adams et al. 1997b) inflation models. In this paper we investigate the flexibility in the determination of cosmological parameters using the much more precise WMAP data, when the usual hypothesis of a *single* power law spectrum is relaxed.

The possible detection of a non-zero Λ through measurements of the Hubble diagram of distant Type Ia supernovae (Riess et al. 1998; Perlmutter et al. 1999) is among the most significant developments in modern cosmology (see Peebles and Ratra, 2003), and has led to the establishment of the ‘concordance model’ with $\Omega_\Lambda \sim 0.7$ and $\Omega_{\text{mat}} \sim 0.3$ (Bahcall et al. 1999). This is quite consistent with the WMAP data for an assumed power-law primordial spectrum; in conjunction with other CMB and LSS datasets the cosmological parameters are determined to be: $\Omega_\Lambda = 0.73 \pm 0.04$, $\Omega_{\text{mat}} = 0.23 \pm 0.04$, $\Omega_b = 0.044 \pm 0.004$, $\Omega_\nu h^2 < 0.0076$ and $h = 0.71 \pm 0.04$ (Bennett et al. 2003). This agreement has led to the widespread belief that the Λ CDM concordance model is now established to high accuracy. However we wish to il-

¹ Technically ‘natural’ means that the required flatness of the potential is protected by a symmetry — here the shift symmetry of a Nambu-Goldstone mode (Freese, Freiman & Olinto 1990). A similar potential has been obtained by imposing a non-Abelian discrete gauge symmetry (Stewart & Cohn 2001).

illustrate that this agreement is crucially dependent on the underlying assumptions concerning the primordial power spectrum and that CMB data do not yet *independently* require a non-zero Λ . Before addressing this issue, let us first examine the situation of the concordance model.

3. Is the concordance model actually concordant?

3.1. Concordance with WMAP data

As mentioned already, Λ CDM with $\Omega_{\text{mat}} = 1$, $h = 0.5$ and $n = 1$ when normalized to COBE (Wright et al. 1992), was found to disagree with the shape of the APM galaxy correlation function (Maddox et al. 1990), as well as the high baryon fraction measured in clusters, which together with the baryon fraction inferred from primordial nucleosynthesis arguments, implied a lower matter density of $\Omega_{\text{mat}} \sim 0.3$ in agreement with local dynamical estimates (White et al. 1993). The subsequent measurements of CMB fluctuations on degree scales however required the universe to be spatially flat and ruled out such a low density matter-dominated Universe. Thus the possible detection of cosmic acceleration in the Hubble expansion of distant supernovae, implying a cosmological constant with $\Omega_{\Lambda} \sim 0.7$, was eagerly seized on as a mean of reconciling the CMB and LSS data. However although this concordance model is consistent with most cosmological observations, its first precision test has come with the WMAP data. The agreement of the concordance model with data as summarised by the WMAP team appears impressive (Spergel et al. 2003). However, there are two facts to keep in mind. First the global χ^2 on the temperature (TT) power spectrum is rather poor — the probability that the model fits the data is only 3%, so strictly speaking the model is rejected at the $\sim 2\sigma$ confidence level! However given possible remaining systematics effects not yet accounted for, the WMAP team concluded that this should not be considered as a serious problem for the concordance model. Allowing for ‘running’ of the spectral index with scale improves the fit somewhat; the data suggest that $n \gtrsim 1$ on the largest scales and $n \lesssim 1$ on small scales.

There is another aspect of the WMAP data that is even more puzzling, viz. the amplitudes of the low C_ℓ s, particularly the quadrupole, is rather small compared to the expectation in the concordance model where the large cosmological constant should boost the anisotropy on large angles. It is well known that the cosmic variance is high on such large angular scales and that Galactic foreground subtraction introduced further uncertainties. Spergel et al. (2003) concluded, from Monte Carlo realisations following two different methods, that the low signal on large scales is not obtained in over 99% of the cases.

However, statistical inferences from the quadrupole amplitude have to be handled with caution. The measured value of $Q_{\text{rms}} = \sqrt{(5/4\pi)C_2} = 8 \pm 2 \mu\text{K}$ corresponds to a variance ($\Delta T_\ell^2 = \ell(\ell+1)C_\ell/2\pi$) of $\Delta T_2^2 = 154 \pm 70 \mu\text{K}^2$ (Bennett et al. 2003), so one might conclude that e.g. an expected $\Delta T_2^2 = 350 \mu\text{K}^2$ is discrepant by about 2σ , which

would be at the 95% c.l. for a gaussian distribution. In properly evaluating this probability however one should take into account the foreground removal technique and its uncertainty, in order to determine the likelihood distribution. Such a distribution is likely to be non-Gaussian and it is therefore possible that the estimation of the goodness-of-fit for the concordance model might be significantly improved in this outlying region. If one instead considers the best-fit concordance model derived by Spergel et al. (2003) to be the true description of the CMB sky, the probability of observing a low quadrupole can be directly estimated. The log-likelihood of C_ℓ^{theo} can be well approximated by (Bartlett et al. 2000):

$$-2 \ln \mathcal{L}(C_\ell^{\text{theo}}) = 5 \times f_{\text{sky}} \times \left[\ln \left(\frac{C_\ell + \aleph}{C_\ell^{\text{theo}} + \aleph} \right) + \frac{C_\ell + \aleph}{C_\ell^{\text{theo}} + \aleph} \right]$$

where the noise is \aleph ($= 3.4 \mu\text{K}^2$ for $\ell = 2$ as quoted in the WMAP data release²), the sky coverage is $f_{\text{sky}} = 85\%$, C_ℓ is the measured amplitude and C_ℓ^{theo} is the value of the best-fit Λ CDM model ($1204 \mu\text{K}^2$ for $\ell = 2$). Given this approximation, one can retrieve the probability distribution of C_2 and thus estimate the chance of observing a low value, following Douspis et al. (2003). For $Q_{\text{rms}} = 8 \mu\text{K}$ this is 4.6%, in agreement with the estimate of Tegmark, de Oliveira-Costa & Hamilton (2003) by a different method (varying the cut CMB sky and considering the best running spectral index model). This indicates that the quadrupole is an outlier at most at the 2σ level.

3.2. Concordance with astronomical data

As discussed already, the concordance model has been built up over time in order to match observations, thus its *a posteriori* agreement with much of the LSS data is not a test. Of course as the quality of data improves the model will be further tested, although the number of free parameters provides some room for adjustment.

3.2.1. Baryon fraction in clusters

Interestingly enough, WMAP has thrown new light on the masses of galaxy clusters and therefore on the inferred baryon fraction. There has been some controversy in recent years concerning the actual masses of X-ray emitting clusters, which are determined by two different methods. One is the application of hydrostatic equilibrium, while the second uses mass-temperature relationships derived from numerical simulations. Systematic differences between the two methods are significant (Markevitch 1998; Roussel, Sadat & Blanchard 2000) and this translates into an appreciable difference in the derived value of σ_8 (Reiprich & Böhringer 2002; Seljak 2002). Furthermore similar differences arise from the use of different theoretical mass functions. The Sheth & Tormen (1999) expression is recognised as providing a satisfactory fit to the mass

² <http://lambda.gsfc.nasa.gov>

function obtained from numerical simulations. Using this for an $\Omega_{\text{mat}} = 0.3$ universe, one finds $\sigma_8 = 0.86$ corresponding to the high mass estimates from numerical simulations, and $\sigma_8 = 0.68$ for the low mass estimates from hydrostatic equilibrium (Vauclair et al. 2003). Clearly the WMAP measurement of $\sigma_8 = 0.9 \pm 0.1$ (Spergel et al. 2003) favours the high mass estimates. The implied baryon fraction (including stars) in clusters is then rather low, slightly below 9% (for $h = 0.7$). This conflicts with the universal baryon fraction of 15% for the best concordance model fit to the acoustic peaks! We note that this discrepancy disappears for $\sigma_8 \sim 0.7$, which is about a 2σ deviation from the best WMAP model...

4. Acceptable Einstein-de Sitter models

Let us now examine whether it is possible to obtain an acceptable CMB power spectrum in an E-dS universe. Clearly to do this we have to deviate from the assumptions of the Λ CDM concordance model regarding the primordial power spectrum. Indeed the WMAP team (Peiris et al. 2003) have already noted that the model fit can be significantly improved (particularly to the outliers at $\ell = 22, 40$ and 200) by allowing for oscillations in the primordial spectrum (Adams, Cresswell & Easther 2001) such as might be induced by phase transitions occurring during inflation (Adams, Ross & Sarkar 1987b). However if we are not to introduce too many new parameters, the simplest modification that can be introduced is perhaps to consider a change in the slope of the spectrum at a particular scale. It is important in this respect to notice that the first and second acoustic peaks span a rather limited range of scales, $\ell \sim 150 - 600$, while the rising part of the first peak covers a much bigger range, $\ell \sim 2 - 200$. Without advocating any specific scenario, it is clearly desirable to examine how a model with *different* power law indices in these two regions compares to the observational data. We therefore focus on models with

$$P(k) = \begin{cases} A_1 k^{n_1} & \text{for } k < k_1, \\ A_2 k^{n_2} & \text{for } k \geq k_1, \end{cases}$$

with a continuity condition ($A_1 k_1^{n_1} = A_2 k_1^{n_2}$). We calculate the CMB power spectrum using the CAMB code (Lewis et al. 2000) and use the WMAP likelihood code (Verde et al. 2003) to determine the quality of the fit.

As we are primarily interested in examining the possible constraints on the cosmological constant, we have restricted our search to models with $\Omega_\Lambda = 0$ but allow a reasonable range for other cosmological parameters (including the optical depth τ to last scattering). The best model we find has $h = 0.46$, $\omega_b = \Omega_b h^2 = 0.019$, $\tau = 0.16$, $k_1 = 0.0096 \text{ Mpc}^{-1}$, $n_1 = 1.015$, $n_2 = 0.806$. As seen in Fig. 1 the calculated power spectrum does very well in fitting the WMAP data and other observations at high ℓ . Interestingly enough a preferred scale of $k \sim 0.01 \text{ Mpc}^{-1}$ was also found by Mukherjee & Wang (2003) who attempted to reconstruct the primordial spectrum in the context of a Λ CDM model, although Bridle et al. (2003)

did not find this using a different method. We wish to emphasise that inspite of having only one more parameter in total, our model has a slightly better χ^2 (on the scalar C_ℓ) than the best concordance model, because of its lower amplitude at low l something (the χ^2 of TE spectrum being identical). In particular, the mean quadrupole C_2 has an amplitude of $844 \mu\text{K}^2$, which has a 13% probability of yielding $Q_{\text{rms}} = 8 \mu\text{K}$. The reason is that E-dS models do not produce integrated Sachs-Wolfe effects as high as in flat models with low matter density and a large cosmological constant. This is pointing in the same direction than the absence of correlation found between X-ray sky and CMB which provides an interesting upper limit on the cosmological constant (cite2002ApJ...580..672B). Thus the issue of whether the observed low signal at $l < 20$ really needs new physics (Spergel et al. 2003; Uzan, Kirchner & Ellis 2003; Efstathiou 2003; Uzan et al. 2003) needs further investigation.

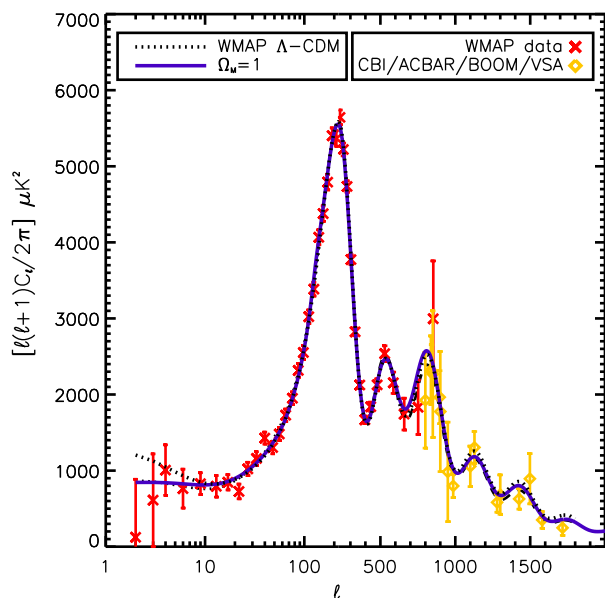


Fig. 1. The temperature power spectrum for the best-fit power-law Λ CDM model (dotted black line) from Spergel et al. (2003), and for our broken-power-law model with $\Omega_\Lambda = 0$ (solid blue line), compared to data from WMAP and other experiments at small scales (Grainge, K. et al. , 2003, Pearson, T.J. et al. , 2002 , Kuo, C. L. et al. , 2002, Ruhl, J. E. et al.). Note the linear scale in l for $l > 200$.

4.1. Why this E-dS model fails

It might appear that our E-dS model with $\Omega_m = 1$, $\Omega_\Lambda = 0$ and $h = 0.46$ must be in conflict with a number of astronomical observations. However, several of these observations which in fact support the Λ CDM concordance

model have been questioned. For example, measurements of Ω_{mat} are mostly local and subject to some controversy. For instance the abundance of high redshift X-ray selected clusters, a global test rather than a local one, systematically leads to high values of Ω_{mat} , well above the best WMAP value (Henry 1997; Sadat, Blanchard & Oukbir 1998; Viana & Liddle 1999; Borgani et al. 1999; Reichart et al. 1999; Blanchard et al. 2000). The only *direct* evidence for a cosmological constant comes from the Hubble diagram of distant Type Ia supernovae, a method which relies on the standard candle hypothesis and on empirical corrections to the observed peak magnitudes on the basis of the observed decay times. However there are systematic differences in the corrections made for the same objects by the two groups (Leibundgut 2000; 2001) which raises legitimate concerns about their validity. Moreover Rowan-Robinson (2002) has argued that when extinction and the luminosity–decay time relation are treated in a self-consistent way, the significance of the evidence for positive Λ is much reduced.

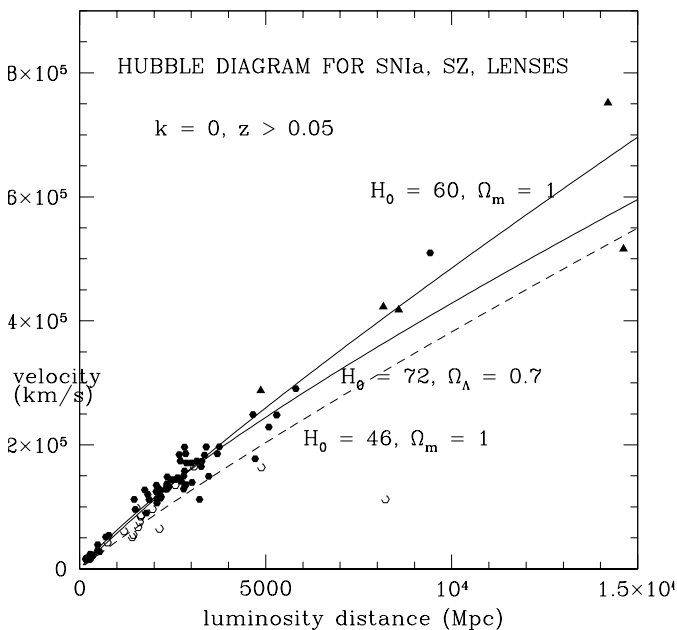


Fig. 2. Velocity versus luminosity-distance for Type Ia supernovae, S-Z clusters and gravitational lens time-delay systems, with $z > 0.05$. All curves shown correspond to flat models and are labelled with the Hubble parameter in km/s/Mpc.

A Hubble constant of $H_0 = 46$ km/s/Mpc would seem to be completely inconsistent with the Hubble Key Project determination of 72 ± 8 km/s/Mpc (Freedman et al. 2001). However there are some details of this work which might merit reexamination:

1. Rowan-Robinson (2003) finds that if a more sophisticated local flow model is used than that of Mould et

al. (2000), there is a reduction of about 2 km/s/Mpc in H_0 .

2. The method of combining the data used by Freedman et al. (2001), viz. estimating H_0 by different methods and then combining the results, does make the outcome somewhat vulnerable to Malmquist bias. Rowan-Robinson (2003) finds that this can also result in overestimation of H_0 by about 2 km/s/Mpc.
3. Between the summary paper of Mould et al. (2000) and that of Freedman et al. (2001), a change in the assumed I-band period-luminosity resulted in an increase of the extinction values in the Cepheid program galaxies, and hence in an average reduction in the distance scale of 4%. This was almost exactly cancelled out by correction for the effects of metallicity on Cepheid distances, of about the same magnitude in the opposite direction. However it is possible that the extinction in the program galaxies has been overestimated and that the correction for the effects of metallicity have been underestimated so these effects do not quite cancel. It would be highly desirable to extend observations of the Key Project Cepheids into the infrared to assess these effects.
4. The assumed extinction in the LMC may be slightly on the low side compared with estimates for hot stars in the LMC by Zaritsky (1999).
5. Finally, it would be highly desirable to confirm the assumed distance to the LMC, preferably by direct geometric methods. All these effects are likely to be small, but it is possible that they may combine in the same direction to significantly reduce H_0 .

It is interesting therefore to note that methods which are largely independent of the LMC and Cepheid distance scale, do tend to give lower values for H_0 . For instance, Sunyaev-Zeldovitch (S-Z) cluster distances, give a value of 54^{+4}_{-3} km/s/Mpc in an E-dS universe (Reese et al. 2002), furthermore any clumping of the gas would lower substantially the actual value. The best determination by the gravitational lens time delay method yields a value of 59 ± 2 km/s/Mpc (Fassnacht et al. 2002). Parodi et al. (2000) have also found a value of 59 ± 4 km/s/Mpc from Type Ia supernovae (see also Branch 2000). Fig 2 shows a compilation of distances to Type Ia supernovae, S-Z clusters and gravitationally lensed systems with $z > 0.05$. The best-fit flat model (not shown) has $\Omega_0 = 0.9 \pm 0.5$ and $H_0 = 60 \pm 11$ km/s/Mpc. Models with $\Omega_{\text{mat}} = 1$, $H_0 = 60$ km/s/Mpc and $\Omega_{\text{mat}} = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 72$ km/s/Mpc are shown (solid lines); both fit the data well. However the model with $\Omega_{\text{mat}} = 1$, $H_0 = 46$ km/s/Mpc (broken line) is clearly a less good fit to the data. In conclusion a Hubble constant in the range 55–65 km/s/Mpc seems entirely plausible at the present time. The value we require, 46 km/s/Mpc, is still below this range, but perhaps only by 1 or 2 σ . We believe the present paper provides a powerful stimulus for further work on the cosmological distance scale.

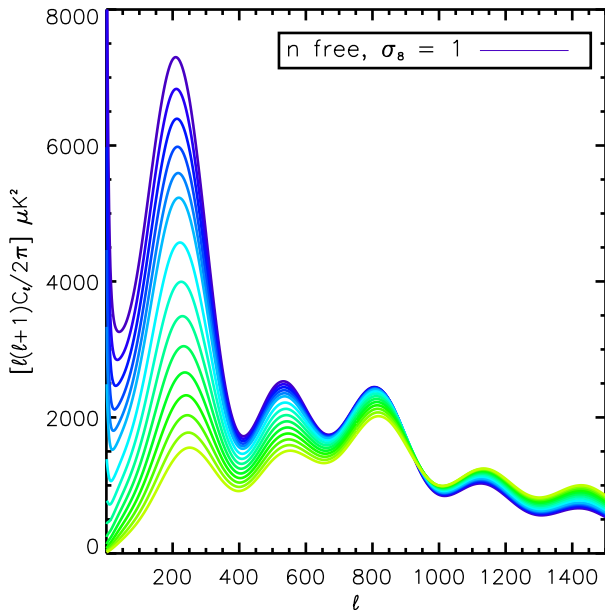


Fig. 3. CMB angular power spectra for models with $\Omega_{\text{mat}} = 1$, $H_0 = 46$ km/s/Mpc and $\omega_b = .019$ normalised to $\sigma_8 = 1$ with different power spectra indexes. Note that they all have the same amplitude around $\ell \sim 900$

There is however one observational constraint that our E-dS model fails to reproduce quite badly, viz. the amplitude of matter fluctuations on cluster scales ($8h^{-1}$ Mpc). This model has an amplitude of $\sigma_8 \sim 1.1$, which is much higher than required to match the local abundance of clusters and weak lensing measurements. The discrepancy is at least at the 5σ level, even taking into account the scatter in the determinations of σ_8 from different analyzes: current estimations for σ_8 from clusters and from weak lensing range from 0.45 to 0.6 (for $\Omega_{\text{mat}} = 1$), consistently with large scale velocity measurements which typically lead to $\Omega_{\text{mat}}^{0.6}/b \sim 0.5$ (see for instance Hawkins et al. 2002). As the WMAP constraints are inexistent on small scales, one could imagine that further modification of the power spectrum could remove this discrepancy, However, an examination of the CMB power spectrum normalized to $\sigma_8 = 1$ for various powerlaw indexes (see Fig. 3) shows that the implied $C_{\ell S}$ on the scale $\ell \sim 900$ is essentially constant. We conclude that the observed amplitude from other experiments (Grainge, K. et al. , 2003, Pearson, T.J. et al. , 2002 , Kuo, C. L. et al. , 2002, Ruhl, J. E. et al.) cannot be matched if σ_8 is significantly smaller than unity and therefore that an E-dS model containing CDM alone cannot accommodate both data sets, *independently* of the shape of the power spectrum.

4.2. Two other cases

In this last section, we examine whether the above discrepancy can be avoided if we do not restrict ourselves to pure CDM models. Specifically, we now have evidence that all the known neutrinos have masses which are rather close to each other, with $\Delta m^2 \simeq 7 \times 10^{-5}$ eV² for the electron and muon neutrinos and $\Delta m^2 \simeq 3 \times 10^{-3}$ eV² for the muon and tau neutrinos, indicated respectively by the oscillation interpretation of the Solar and atmospheric neutrino anomalies (see Gonzalez-Garcia & Nir 2003). Moreover the direct kinematic limit on the neutrino mass from the Mainz and Troitsk tritium β -decay experiments is 2.2 eV (see Weinheimer 2002). The addition of massive neutrinos is well known to damp the power spectrum on scales smaller than their free-streaming length and thus to lower σ_8 . We have therefore introduced three degenerate neutrinos of mass 0.8 eV and find the following model provides an acceptable fit: $h = 0.46$, $\omega_b = \Omega_b h^2 = 0.021$, $\tau = 0.10$, $k_1 = 0.009$ Mpc⁻¹, $n_1 = 0.98$, $n_2 = 0.87$, $\Omega_\nu = 0.12$. The amplitude on clusters scales is perhaps still too high at $\sigma_8 = 0.64$, but it is certainly premature to rule out this model on this single issue.

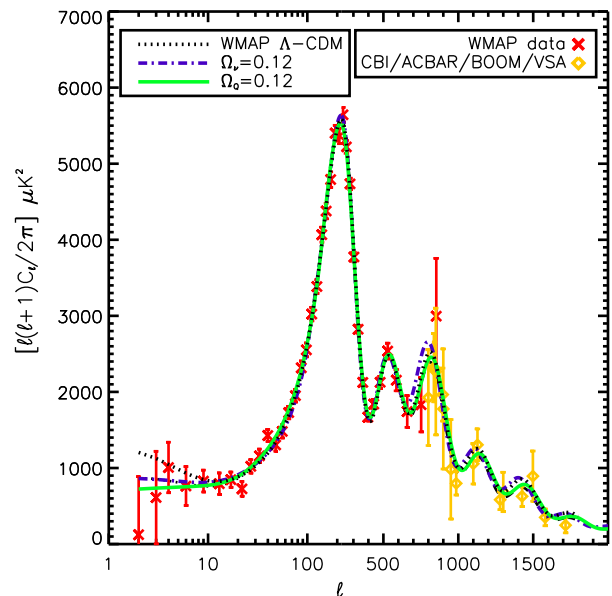


Fig. 4. The temperature power spectrum for the best-fit power-law Λ CDM model (dotted black line) from Spergel et al. (2003), and for our broken-power-law models (both having $\Omega_\Lambda = 0$) with $\Omega_\nu = 0.12$ (dot-dashed blue line) and $\Omega_Q = 0.12$ (solid green line), compared to data from WMAP and other experiments (Grainge, K. et al. , 2003, Pearson, T.J. et al. , 2002 , Kuo, C. L. et al. , 2002, Ruhl, J. E. et al.).

In a second model we introduce a small amount of ‘quintessence’ with $w_Q = 0$. Such possibility arises natu-

rally as an attractor solution of a simple exponential potential: $V = M_p^4 \exp(-\lambda\Phi/M - p)$. Such possibility is well motivated from various particle physics theories (Ferreira & Joyce, 1998), but have not been retained because a large contribution to the total density of the universe is excluded (Ratra & Peebles, 1988). However, this model with $\Omega_Q \sim 0.1$ has been argued to lead to a good agreement with observations (Ferreira & Joyce, 1997). Indeed, we find that such model leads to a lack of power at small scales compared to pure cold dark matter and provides an acceptable fit to the CMB data for the following parameters: $h = 0.45$, $\omega_b = \Omega_b h^2 = 0.019$, $\tau = 0.10$, $k_1 = 0.012 \text{ Mpc}^{-1}$, $n_1 = 1.00$, $n_2 = 0.90$, $\Omega_Q = 0.12$ and provide a good amplitude of matter fluctuations on cluster scale $\sigma_8 = 0.5$.

For both cases, the temperature-polarization spectrum was also found to be in good agreement with WMAP data. The baryonic content $\omega_b = \Omega_b h^2 = 0.019$ is in perfect agreement with current BBN estimates. The baryon fraction derived in these two models is of course rather low ($f_b \sim 10\%$) but consistent with recent estimations (Sadat & Blanchard 2001). It is also necessary to examine the agreement of these models with LSS data, in particular the power spectrum obtained from studies of galaxy clustering and the Lyman- α forest. For this purpose we adopt a bias parameter given by $b = 1/\sigma_8$. As seen in Fig. 5, both models are in agreement with the APM power spectrum (Baugh & Efstathiou 1993; Peacock 1997), the 2dFGRS power spectrum (Percival et al. 2001; Tegmark, Hamilton & Xu 2002) and the Ly α forest (matter) power spectrum (Croft et al. 2002) which has been used recently to set interesting constraints on models of large scale structure (Douspis, Blanchard & Silk 2001). The model with massive neutrinos provides a particularly good description of LSS data. Such a model has already been considered by Elgaroy & Lahav (2003) to find a good fit to the 2dFGRS data, but maintaining a constant power law index on large scales as they do then gives a very poor fit to the WMAP data. We emphasize that although our model is apparently in conflict with the upper bound of $\Omega_\nu h^2 < 0.0076$ quoted by Spergel et al. (2003), this latter bound was obtained with much restrictive assumptions, hence might not be considered as being sufficiently conservative.

5. Discussion and Conclusions

We have shown that when the assumption of a single power law for the primordial fluctuation spectrum is relaxed, models with zero cosmological constant can be found which fit the CMB data as well if not better than the best concordance model. This is a clear and direct indication that the CMB data alone does not require the introduction of a non-zero cosmological constant. However, pure Cold Dark Matter models fail to simultaneously match both the CMB data and the amplitude of matter fluctuations as indicated by clusters, velocity field amplitude and weak lensing measurements. Despite this problem, we have further shown that acceptable Einstein-de

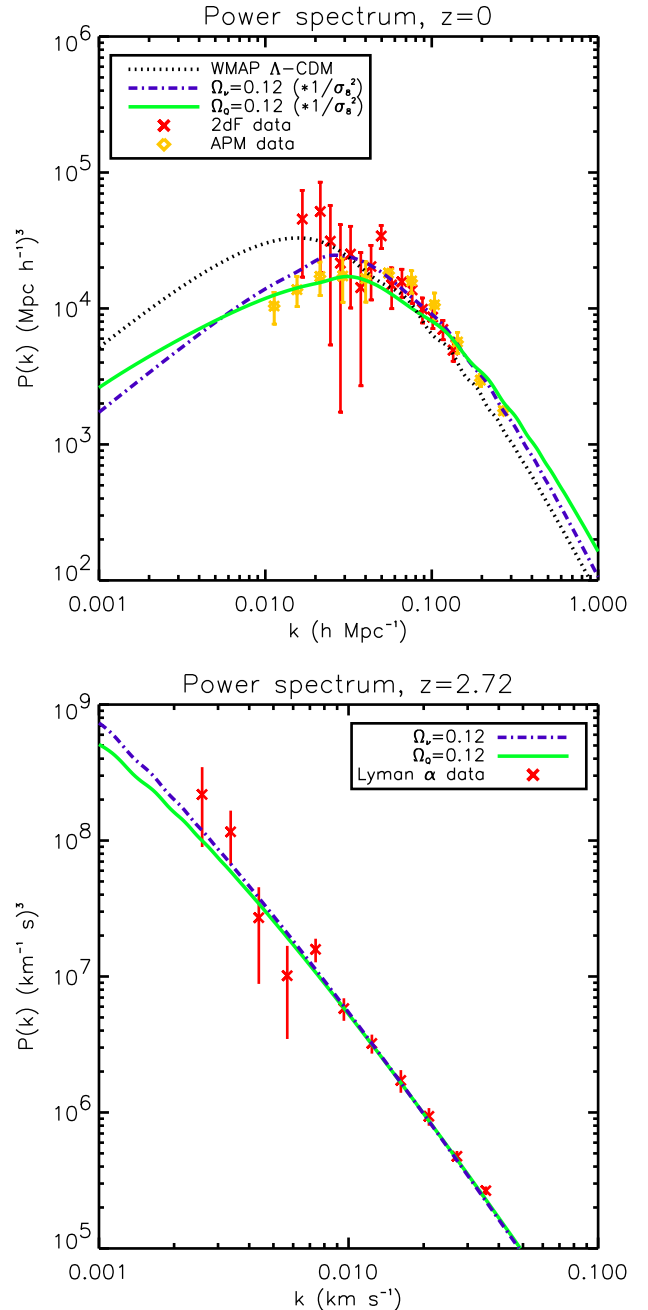


Fig. 5. The power spectrum of large scale structure at $z = 0$ and $z = 2.3$ for our two E-dS models with $\Omega_\nu = 0.12$ (dot-dashed blue line) and $\Omega_Q = 0.12$ (solid green line). Note that the Lyman- α data have been shifted downwards by 20% (corresponding to the 1σ uncertainty in the calibration).

Sitter models are possible provide they comprise a small amount of a dark component which does not cluster on small scales, such as relic neutrinos with mass of order eV or a quintessence contribution of the order of $\Omega_Q \sim 0.1$. These models have a low, but as we have argued, not unacceptable, Hubble constant.

We conclude that existent CMB and LSS data actually *imply* the existence of a dark component beyond cold dark matter, with a density contribution of at least about 10% of the critical density. This component might have an equation of state corresponding to conventional (pressureless) matter. Such models reproduce quite well the observed properties of large scale structures of universe without further adjustment. The fundamental consequence is that Einstein-de Sitter models can be considered as still acceptable. Although they conflict with some astronomical data, we have argued that none of these data is established beyond doubt. These solutions offer the advantage to avoid the severe coincidence problem associated with a classical cosmological constant.

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