COSMOLOGICAL IMPLICATIONS OF THE FIRST YEAR WILKINSON MICROWAVE ANISOTROPY PROBE RESULTS

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The Wilkinson Microwave Anisotropy Probe (WMAP) team has recently analyzed and released the first-year data. We will review the implications for cosmology of these results. The highlight is that cosmology now has a standard cosmological model. With only 6 parameters the model fits not only WMAP data remarkably well, but also a host of other astronomical observations. We also present the results on neutrino mass limits and on dark energy properties from a joint likelihood analysis of WMAP data with small-scale CMB experiments and large-scale structure surveys. The data and supplementary information are publicly available and can be found on the experiment web site at http://lambda.gsfc.nasa.gov.

1. Introduction

The first year results from the Wilkinson Microwave Anisotropy probe (WMAP) were announced on February 11 2003. On the same day the telescope was renamed in honor of Prof. David Wilkinson, member of the science team and pioneer in the study of cosmic microwave background (CMB) radiation. WMAP was launched from Cape Canaveral on June 30 2001. It arrived at the L2 Lagrangian point in October 2001 (in practice the satellite was stable enough for CMB data-taking to commence at the beginning of August). The primary goal of the WMAP mission is to produce a high-fidelity all-sky polarization-sensitive map of the CMB radiation to determine the cosmology of our Universe. After a year of observation it has produced a full sky map of the microwave sky in 5 frequencies, with a resolution a factor 30 higher than the previous full sky map as produced by the COBE satellite in 1992 (see Fig. 1). This is the cleanest picture of the early Universe; the structures on the CMB –the pattern of hot and cold spots– carry information about the composition, geometry, age, etc. of our Universe. The WMAP data release was accompanied by 13 papers[1−13] here we summarize the main results.

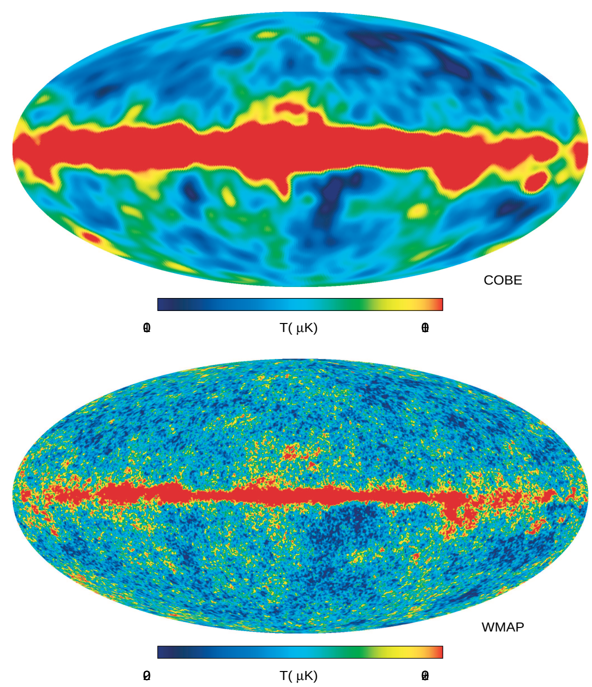

Figure 1. A comparison of the COBE 90 GHz map (upper panel[14]) and the W-band WMAP map (lower panel[1]).

2. What does WMAP Measure that contains Cosmological Information?

WMAP data have yielded new results relative to several different epochs in the history of the Universe. With unprecedented precision we now know that CMB light comes to us from 380,000 years after the big bang, the first stars appeared 200 million years after the big bang, and the the Universe is 13.7 Gyr old. We have also learnt about the Universe composition and the properties of the seeds of cosmological structure formation.[1] What is WMAP measuring that contains all this cosmological information?

By looking at the CMB we see the leftover heat from the big bang; the hot and cold spots in a CMB temperature map correspond to fluctuations in the underlying density field.

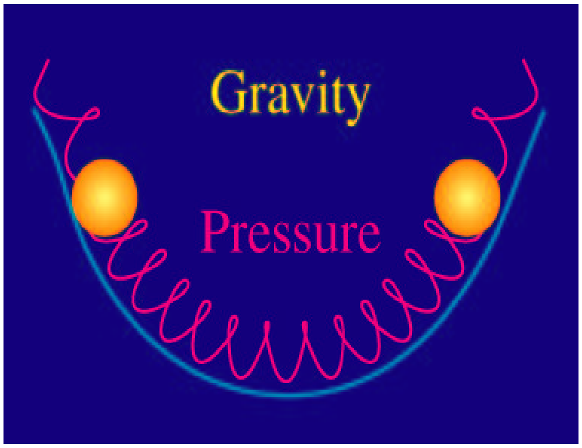

Figure 2. From http://background.uchicago.edu/∼whu/ intermediate/intermediate.html: analogy for the acoustic oscillations in the baryon-photon fluid.

The radiation that we see from the CMB comes from the last scattering surface: when the Universe recombines, the CMB photons can travel to us virtually unperturbed thus giving us a snapshot of the photon-baryon fluid in the early Universe. On large scales, where no physical processes could have taken place, the anisotropies that we see correspond to "primordial ripples", the seeds from which the action of gravity grew cosmological structures such as galaxies and clusters of galaxies that we observe today.

On smaller scales two competing processes are at play in the photon-baryon plasma: photons exert radiation pressure which contrasts the compression from gravity resulting in acoustic oscillations. This can be visualized[15] imagining two masses connected by springs in a potential well (Fig. 2). The potential well represents an overdensity region, the depth of the potential well depend on the total mass (actually energy-density); the spring represents the radiation pressure while the masses represent the baryons. Of course, underdense regions can be thought of as potential "hills" in the same analogy.

The sound waves in the photon-baryon plasma stop oscillating at recombination, when support from radiation pressure stops. It is a snapshot of these oscillations that we see in the CMB. In other words by looking at the CMB we are "seeing sound".[16]

We can push the analogy further: as a violin string has a fundamental mode and overtones which depend on the length of the string, so the horizon size at the last scattering surface defines a fundamental mode (and its overtones) for the sound waves in the photon-baryon plasma. Thus the angular power spectrum[a] of the temperature anisotropies in the CMB carry the imprint of the fundamental mode and its overtones. The modes that the snapshot catch at extrema of the oscillations correspond to enhanced temperature fluctuations on scales given by the mode's wavelength. While the fundamental mode corresponds to a compression, the first overtone corresponds to a rarefaction and so on (this is easy to visualize by going back to the analogy of the springs and masses in a potential well).

These ideas are not new: they were worked out independently and almost simultaneously, on the two sides of the iron curtain in 1970.[17,18] However it was not until more than 20 years later that it was clear that one could learn about cosmology by looking at these acoustic fluctuations in details.[19−21]

How would one extract cosmological information from a CMB map in practice? First, we want to compress the CMB maps, for WMAP for example these are Mega-pixel maps, to study cosmology. The details of our method can be found in Hinshaw *et al.* (2003).[3] We can express the temperature fluctuations in the CMB sky ($\delta T(\theta, \phi)$, where $(\theta,\, \phi)$ denotes the position angle) by expanding it in spherical harmonics:

$$\delta T(\theta, \phi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\theta, \phi)\ . \qquad (1)$$

If the anisotropies form a gaussian random field[b], that is if the real and imaginary parts of each $a_{\ell m}$ are independent normal deviates, all the statistical information is contained in the *angular power spectrum*:

$$C_\ell = \frac{1}{2\ell+1} \sum_m |a_{\ell m}|^2\ . \qquad (2)$$

Figure 3 shows the CMB temperature anisotropy angular power spectrum before and after WMAP. In the left panel of Fig. 3 the points with error-bars correspond to different CMB experiments, in the right panel, WMAP band-powers data are shown with the error bar due to instrumental noise. In both panels the solid line is the best fit model to WMAP

[a] Harmonic transform of the two point correlation function.
[b] We find no evidence for deviation from gaussianity.[6]

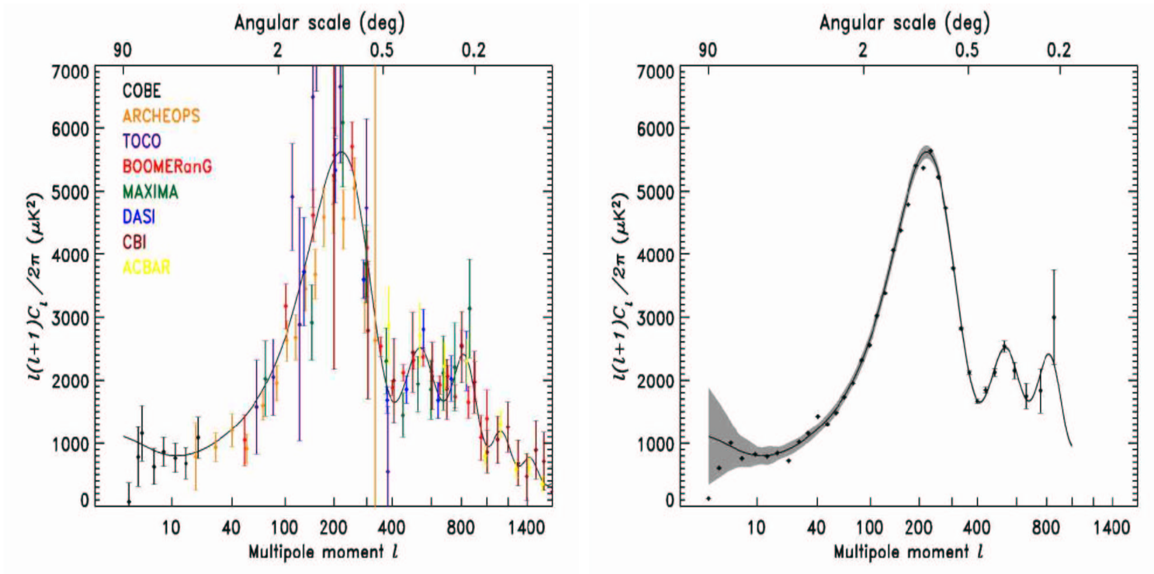

Figure 3. Left:[3] compliation of the CMB angular power spectrum before WMAP, the solid line is the best fit model for WMAP data. Right:[3] WMAP angular power spectrum: the gray band is the cosmic variance error-bar while the error-bars on the data points are the noise-error bars. Notice the first peak (corresponding to a compression) and the second peak (corresponding to a rarefaction).

data. The gray area in right panel of Fig. 3 shows the cosmic variance error. Cosmic variance error is due to the fact that we can observe only one Universe. Given a cosmological model with some specified cosmological parameters and thus a power spectrum, different realizations of the CMB sky drawn from that model will have slightly different power spectra. Since the CMB we can measure is just one realization of the true (unknown) underlying model, there is some cosmic variance error associated with the best fit C_ℓ.

Some features are evident from the right panel of Fig. 3: on large angular scales (small multipole ℓ), to good approximation we see the primordial ripples. On smaller scales (larger ℓ) we see a series of "acoustic peaks" corresponding to the acoustic oscillations in the photon-baryon fluid. The peak on scales of about a degree ($\ell \sim 200$) corresponds to the fundamental mode: these scales are so large that at recombination the mode had time to go through only one compression, the second peak corresponds to the first overtone and on these scales the mode went through a compression and a rarefaction and was "frozen" then; the third peak corresponds to a compression and so on. Since the horizon size at the last scattering surface is a well defined quantity, a "standard rod", the angle it subtends must be related to the geometry of the space between the observer (WMAP satellite at L2, today) and the last scattering surface (at $z \sim 1100$). If a standard rod subtends an angle, say, α in a flat, euclidean space (you can visualize this in 2 dimensions as a flat sheet of paper), it will subtend an angle **larger** than α in a positively curved, closed space (which you can visualize in 2 dimensions as the surface of a sphere) and an angle **smaller** than α in a negatively curved, hyperbolic space. Since, in Einstein's general relativity theory, it is the matter-energy content that shapes the geometry of space-time, the position of the first acoustic peak tells us about the total matter-energy density content of the Universe. Cosmologists use the parameter Ω_{tot}: the ratio of the matter-energy density to the critical one necessary to make the geometry of space flat.

The height of the first peak must also be related to the depth of the potential wells as deeper wells will create stronger compression. Since the depth of the potential wells depend on the amount of mass, the height of the first peak tells us Ω_{matter}: the ratio of the matter density to the critical matter-energy density. Notice here that Ω_{tot} need not coincide with Ω_{matter}, as vacuum energy (or Einstein's

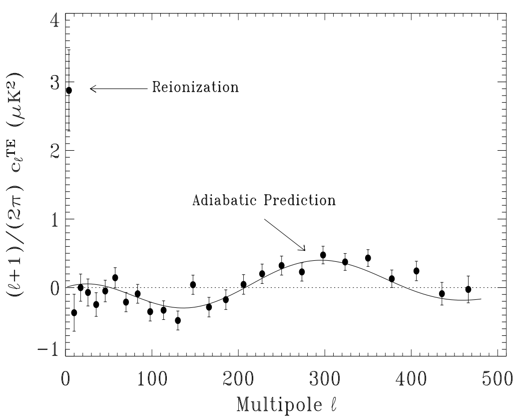

Figure 4. The temperature-polarization cross correlation power spectrum.[12]. The solid line is the prediction from the temperature data for adiabatic initial conditions. The excess power at $\ell < 10$ is due to early star formation.

biggest blunder, a cosmological constant) would contribute to Ω_{tot} by shaping space-time, but not to Ω_{matter}.

The analogy with the oscillations of the spring with a mass attached will help us understand that the relative height of the first and second peak tell us about the baryon content of the Universe. A larger baryon content correspond to a larger mass attached to the spring (while it is the total mass content, baryonic and non-baryonic that determines the depth of the potential wells): the larger the baryon content the bigger would be the ratio between compression and rarefaction, thus larger relative height of the first to second peak. [c]

2.1. *Information in the Polarization*

Cosmological information is not just enclosed in the temperature anisotropy but also in the polarization of the CMB radiation. The CMB polarization is produced by Thompson scattering of a quadrupolar radiation pattern. At decoupling the quadrupole is produced by velocity gradients. Since both the velocity field and the temperature anisotropies are created by density fluctuations, a component of the polarization should be correlated with the temperature anisotropy. In particular on scales ~ 1 degree, primordial adiabatic initial conditions, such as those set up by inflation, predict an anti-correlation between temperature and polarization signal. This anti-correlation is not expected if initial conditions are of a different nature; for example isocurvature perturbations or perturbations originating from a casual seed model (such as e.g. topological defects). For primordial adiabatic initial conditions the temperature power spectrum gives precise predictions for the temperature-polarization cross correlation power spectrum. This prediction is exactly what we have seen in the data[12] (see Fig. 4): this is a triumph for the standard cosmological model.

I should note here that the WMAP team reported the temperature-polarization cross correlation. Last year, the first detection of the CMB polarization signal was announced;[22] now the measurement is so precise that the temperature-polarization cross correlation data can be used to learn about cosmology.

There is a second effect that can be seen in the polarization (TE) data: an excess signal on the largest scales, which is not predicted by the temperature data alone. If the first stars form at high redshift ($z \sim 20$), their light reionizes the Universe; free electrons scatter CMB photons introducing some optical depth (denoted by τ) and uniformly suppressing the power spectrum of the temperature fluctuations by $\sim 30\%$. Free electrons see the local $z \sim 20$ CMB quadrupole and polarize the CMB at large scales where no other mechanism of polarization operates. The excess polarization signal is a signature of the formation of the first stars in the Universe, such a large signal implies that stars started forming much earlier than most people previously thought.[12]

3. Interpretation of WMAP Data

Without going into technical details of the data analysis,[8] let us briefly outline the method of the analysis before going into the results. The analysis path follows these steps:

a) select a set of cosmological parameters;

b) compute for these parameter the "model" power spectrum C_ℓ^{theory}: for this step we use the publicly available software CMBFAST[23] but other packages are also avalilable;

c) compare to the measured power spectrum and compute the likelihood; and

[c]For more details see Page *et al.* (2003).[9]

Table 1. LCDM best fit parameters to WMAP data;[5] left: format for physicists, right: format for astrophysicists. All errors are 1σ.

Dark matter	$(2.25 \pm 0.38) \times 10^{-27}\mathrm{kg/m^3}$	Ω_c	0.26 ± 0.07
Atomic density	$(2.7 \pm 0.1) \times 10^{-7}\ \mathrm{cm^{-3}}$	$\Omega_b h^2$	0.024 ± 0.001
Age	13.4 ± 0.3 Gyr	h	0.72 ± 0.05
σ_8	0.9 ± 0.1	σ_8	0.9 ± 0.1
n_s	0.99 ± 0.04	n_s	0.99 ± 0.04
z_{reion}	17	τ	0.17 ± 0.04

d) repeat to find confidence regions.

With this procedure WMAP data can be analyzed alone and/or in combination with other, complementary, data sets.

The simplest (and most popular) cosmological model (the so called LCDM model) has 6 parameters, and corresponds to a flat, low density Universe composed of baryons, dark matter and dark energy. The 6 parameters are: the dark matter density (parameterized by Ω_c), the physical baryon density ($\Omega_b h^2$), the Hubble parameter ($H_0 = 100$ Km/s/Mpc$h$), the spectral slope of the primordial power spectrum (n_s), the amplitude of fluctuations (parameterized by the present-day r.m.s. fluctuations smoothed on 8 Mpc/h spheres σ_8), and the optical depth to the last scattering surface τ). For physicists these 6 parameters are equivalent to a different set of more familiar parameters (see Table 1). Following Occam's razor, we start analyzing this simple model and then add complications (i.e. extra parameters) one at the time. For this model WMAP data (temperature and temperature-polarization spectra) tell us that:

a) there is no evidence for deviations from gaussianity of the CMB maps:[6] the CMB looks gaussian (thus supporting our initial assumption that all statistical information about CMB anisotropies of the mega-pixel maps can be "compressed" into a power spectrum);

b) 15% of the CMB light was rescattered since the Universe reionized early: the estimated reionization redshift is $z \sim 20$ or 200 million years after the Big Bang;[12] and finally, probably the most important result

c) the simple, flat, LCDM model fits remarkably well this new set of observations of unprecedented precision: only 6 parameters fit 1346 data points (or, to be even more ambitious, one could say that 6 parameters fit the million-pixel maps).[5]

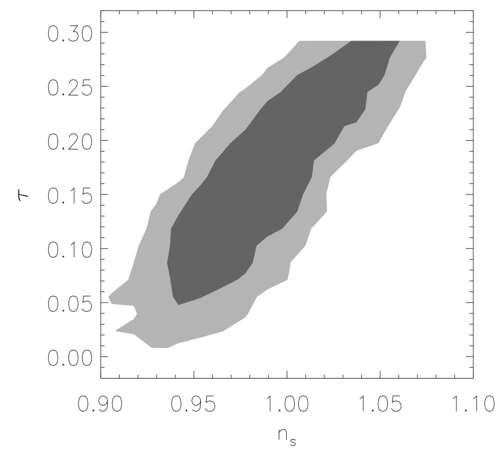

Figure 5. Main degeneracy among cosmological parameters for WMAP data.[5] Degeneracies increase the error-bars on marginalized quantities, but this will quickly improve with more years of operation.

The best fit values for the cosmological parameters are reported in Table 1.

Another (derived) parameter that might be of interest is the baryon-photon ratio:[5] $\eta = 6.5^{+0.4}_{-0.3} \times 10^{-10}$.

Remarkably, these parameters fit not only WMAP data and other CMB experiments, but also a host of other cosmological observations. For example the Hubble parameter constraint (a measurement of the Universe's expansion rate), is in agreement with the Hubble space telescope measurement obtained from observations of stars of known intrinsic luminosity in nearby galaxies; and the age determination is in good agreement with other determinations based on the ages of the oldest stars.

When using WMAP data alone some degeneracies among cosmological parameters remain, the main degeneracy being between the primordial power spectrum spectral slope and the optical depth to the last scattering surface (see Fig. 5). Degeneracies among cosmological parameters increase the error-bars on marginalized quantities, but this will quickly improve with more years of operation.

4. Combining WMAP Data with other Data Sets

WMAP data can be combined with external, complementary data sets. In doing so we can achieve two goals. First, and more important, we can test the consistency of the cosmological model; second, if all data sets are consistent with the model, we can lift degeneracies among cosmological parameters.

We combine WMAP data with small-scale CMB experiments (CBI[25,26] and ACBAR[27]), with the power spectrum of large-scale structure data probed by the Anglo-Australian Two degree field galaxy redshift survey (2dFGRS[28,29]) and by the Lyman-alpha forest,[30,31] although the results presented here have been obtained without the Lyman-alpha data. The data set compilation is shown in Fig. 6. While the CMB probes the Universe on large scales and at redshift $z \sim 1100$, the 2dFGRS galaxy survey provides a three-dimensional map of the galaxy distribution in the local Universe, it probes smaller scales and $z \sim 0$. The Lyman-alpha forest is a series of absorption features in the spectra of distant quasars, caused by the cosmological structures intervening along the line of sight: from the correlation properties for the absorption lines it is possible to reconstruct the three-dimensional power spectrum of these intervening structures at $z \sim 3$ and probe scales much smaller than those accessible from CMB or galaxy surveys. As Fig. 6 illustrates, these observables are complementary in scale and in redshift.

5. Beyond the Simple LCDM Model

Armed with the statistical power of these external data sets, we can try to test models beyond the simple six-parameter LCDM model. For example we can drop the assumption that the universe is spatially flat, and introduce an extra parameter Ω_Λ, where $\Omega_m + \Omega_\Lambda = \Omega_{tot}$, or we can drop the assumption that neutrinos are nearly massless.

5.1. *Flatness*

If we allow the geometry of the universe to deviate from flat but assume that the dark energy component is in the form of a cosmological constant, we obtain the constraints shown in Fig. 7.

As Fig. 7 shows CMB data alone (orange confidence region – from top left corner to bottom right corner – show the joint 2σ confidence level in the Ω_m-Ω_Λ plane) favors flat or nearly flat models. But dropping the flatness assumption creates new degeneracies among cosmological parameters: for example the Ω_m constraint is now weaker. The addition of external data sets lift this degeneracy: the (darker) red confidence contours are for CMB and Hubble space telescope constraint on the Hubble parameter. The green (from botton left corner to upper right corner) confidence contours are the 1, 2 and 3σ confidence levels obtained from supernovae data (see R. Kirshner's presentation). The blue (vertical) contours are the 1, 2 and 3σ constraints obtained from analysis of the 2dFGRS.[32] In total we obtain a constraint on the flatness of the Universe $\Omega_{tot} = 1.02 \pm 0.02$ (68% confidence level). It is quite remarkable that different measurements that rely on different physics, different observables and were carried out independently by different research groups, agree to better than 1σ level! One conclusion that we can draw from this is that we (and all chemistry) are a small minority (4%) of the Universe: dark energy makes up 73% and dark matter 23%.

5.2. *Dark Energy Properties*

Since we find no evidence for deviations from a flat geometry, we can assume $\Omega_{tot} = 1$ and proceed to constrain the properties of dark energy. Dark energy properties can be parameterized by its equation of state $w = -P/\rho$ where P denotes pressure and ρ the density. For a cosmological constant $w \equiv -1$ while for the alternative candidate, "quintessence", a dynamic, time evolving and spatially varying energy component, $w \neq -1$. Although in principle for a quintessence model w need not to be constant, we will assume, as a first approximation, that it is constant in time; the w measurement will thus refer to an "effective" value for w, some sort of weighted

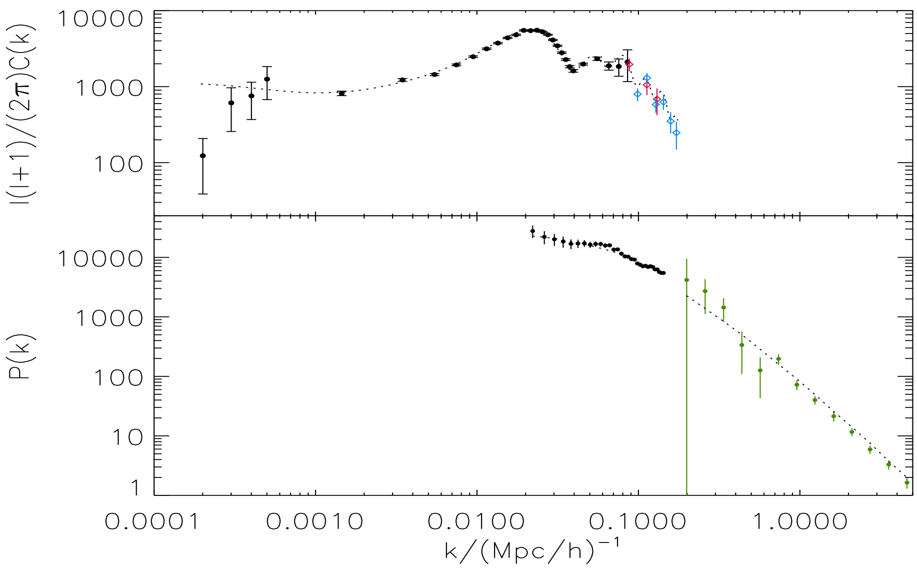

Figure 6. Top panel:[24] WMAP, small-scale CMB experiments (CBI and ACBAR), the multipole ℓ has been converted in wavenumber k. Bottom panel:[24] 2dFGRS data and Lyman-alpha. The data set considered are complementary in scale and in redshift. The dotted line is the best fit model to WMAP data. The extrapolation of this model to low redshift and smaller scales fit the data remarkably well.

average of the w values from $z = 0$ to $z = 1100$. In Fig. 8 we show the joint likelihood contours in the $w - \Omega_m$ plane for the supernovae data (green confidence region; from upper left to lower right), CMB, that is WMAP + CBI + ACBAR (orange; from bottom left to top right) and CMB+Hubble constant determination from the Hubble space telescope (darker region). As Fig. 8 shows, by combining different data sets we find no evidence for the dark energy being something different from a cosmological constant. Our constraint is:[5] $w = -0.98 \pm 0.12$.

5.3. *Neutrino Mass*

Up to now we have assumed that neutrinos are (nearly) massless, but we can try to constrain the neutrino mass in the context of a flat LCDM model. From current observations the CMB alone is not sensitive to the neutrino mass. The left hand side panel of Fig. 9 shows the – virtually indistinguishable – CMB power spectra for 2 models: one where neutrinos are massless the other one where there are three degenerate neutrinos species each of them with a mass of 0.6 eV. Neutrinos stream freely out of the potential wells thus if they have mass they tend to erase fluctuations on small scales, and thus to suppress the growth of cosmic structures on those scales. The right-hand-side of Fig. 9 shows the matter power spectrum (at $z = 0$) on scales probed by large scale structure surveys, for the same two models; the error bars show the typical error for a data point on those scales. The shape and amplitude of the large-scale structure power spectra are different in the two models and it is clear that the two models can be easily distinguished if the matter power spectrum amplitude is known. All we can measure for example from a galaxy survey, however, is the power spectrum of the galaxy distribution and, in principle, it is not guaranteed that it will coincide with that of the underlying dark matter. Nevetheless the analysis of higher-order correlations[32] of the 2dFGRS shows that it is possible to constrain the relation between clustering of mass and that of galaxies. In other words, we have a way to measure the power spectrum of galaxies, infer that of matter and use this to place constraints on the neutrino mass. In doing so we obtain: $\Omega_\nu h^2 < 0.0067$ at the 95% confidence level when combining the CMB data (WMAP+CBI+ACBAR) with 2dFGRS.[5] For three degenerate neutrino species, this implies $m_\nu < 0.23$ eV. If we add the Lyman-alpha data this constraint remains virtually unchanged.

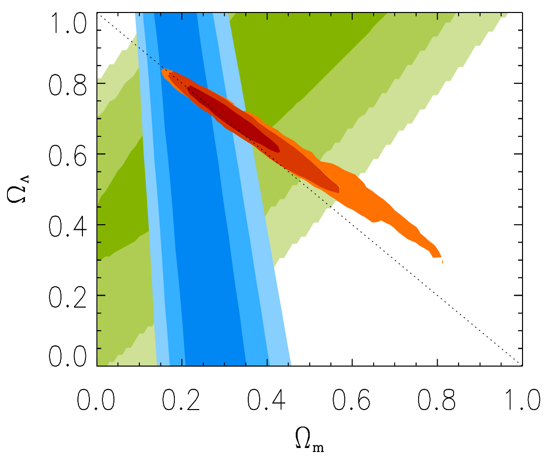

Figure 7. Joint likelihood contours in the $\Omega_m - \Omega_\Lambda$ plane:[24] Green (from botton left corner to upper right corner) Supernovae (see R. Kirshner's presentation); orange (from top left to bottom right) CMB that is WMAP+CBI+ACBAR, only the 2σ level is visible, the 1σ level coincide with the 2σ level (light red) for CMB+Hubble parameter determination from the Hubble space telescope; blue (vertical) 1, 2, and 3σ contours from the 2dFGRS. These different, independent data sets seem to agree to better than the 1σ level.

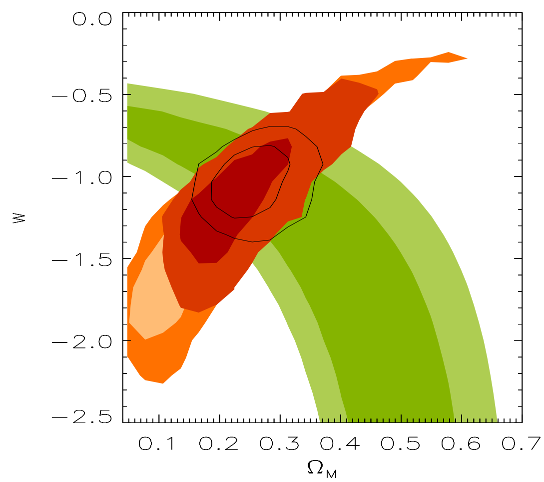

Figure 8. Joint likelihood contours in the $w - \Omega_m$ plane:[5] Green (from upper left to lower right) Supernovae (see R. Kirshner contribution); orange (from bottom left to top right) CMB (that is WMAP+CBI+ACBAR), dark red CMB+Hubble constant determination from the Hubble space telescope. Transparent contours are joint for all data sets: we see no evidence for deviation from $w = -1$.

6. Intriguing Features

We find that there are two intriguing discrepancies. First, given the best fit model, the reduced chi-square for the temperature power spectrum is 1.09: only in 3% of the cases, if the true underlying model was given by our best fit model, a realization of it in the sky would have a reduced chi-square as large or larger. While it is possible to explore the consequences for the inflationary paradigm of this finding,[7] it might be that the excess chi-square could be due to our underestimating the covariance matrix at the percent level. This effect will be accounted for in a forthcoming work, and will allow us to decide whether the "bad" reduced chi-square is due to inadequacy of our modeling or a sign of new physics. The other intriguing discrepancy is more evident from the 2 point correlation function of the temperature data (Fig. 10): there seems to be a lack of correlation at scales larger than about 60 degrees (black/darker line), a feature already evident from the COBE data. This lack of power on large scales manifests itself in the power spectrum as the multipoles at $\ell = 2$ and 3 being much lower than the theory prediction (see Fig. 3). The statistical significance of the lack of large-scale power is difficult to interpret from Fig. 10 because of correlations between data points; Monte Carlo simulations are needed to assess the statistical significance of any deviation from the LCDM model[5,1] (green/lighter line). We find that in $\sim 0.2\%$ of the cases the LCDM model shows this lack of large-scale power. If the Universe was finite and smaller than the volume within the decoupling surface then one would expect to see a lack of correlation on very large scales, similar to what we see here. However, if the Universe was finite there should be several pairs of matched circles detectable in the sky.[33,34] In two independent searches, none has been found.[35,36]

7. Conclusions

We have presented the highlights of the implications for cosmology of the WMAP first year results. The standard LCDM model works remarkably well: only 6 parameters fit not only WMAP data but also small-scale CMB experiments (CBI and ACBAR) and large-scale structure data (2dFGRS, Lyα forest power spectrum) and derived parameters such as the age of the Universe, the Hubble constant value or

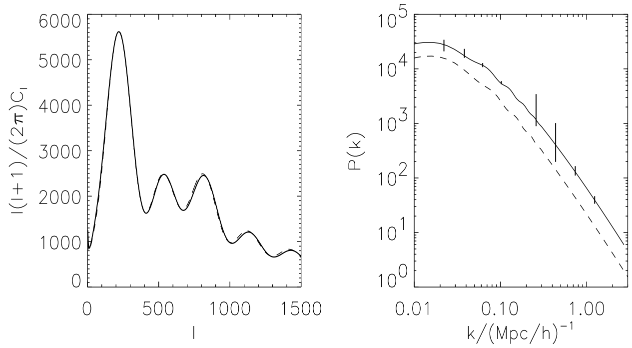

Figure 9. Two models:[8] one with massless neutrinos the other with three degenerate neutrino species each with a mass of 0.6 eV. These two models are virtually indistinguishable from the CMB power spectrum (left) but the matter power spectra are very different on scales probed by large-scale structure surveys (right). It is clear that the two models can be easily distinguished if the matter power spectrum shape and amplitude are known.

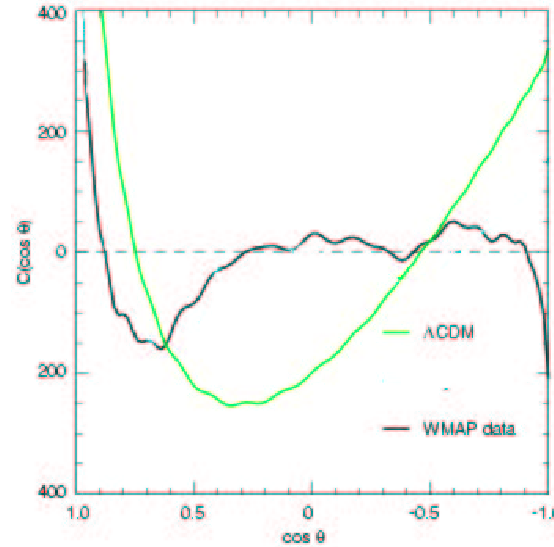

Figure 10. The correlation function for WMAP data (black/darker line), and the best fit LCDM model (green/lighter line).[5] In the WMAP data there seems to be a lack of correlation at scales larger than about 60 degrees compared to the prediction of the LCDM model.

the amplitude of fluctuations are in excellent agreement with other independent astrophysical determinations. We have extrapolated the WMAP observations at $z = 1088$ forwards in time to $z \sim 3$ (Lyα power spectrum) and $z \sim 0$ (e.g. 2dFGRS power spectrum, Supernovae data, HST key project data). This extrapolation describes the observations so well that we feel confident to attempt to extrapolate it backwards, to $z \gg 1088$, and try to shed some light on the dynamics of inflation.[7]

Cosmology is now at a similar stage to particle physics three decades ago, when we converged on the current standard model. The Standard Model of particle physics fits a wide range of data, but does not answer many fundamental questions e.g. "what's the origin of mass?" Cosmology has now a standard model, the LCDM model: a flat universe composed of non-baryonc matter, baryons and vacuum energy. The standard cosmological model has deep open questions e.g. "what's dark energy?", "what's dark matter?" Over the coming years improving CMB, large-scale structure, gravitational lensing and supernovae data etc. will provide ever more rigorous tests of the model.

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The data set, the WMAP temperature and temperature-polarization angular power spectra are available at http://lambda.gsfc.nasa.gov. If using these data set please refer to Hinshaw *et al.* (2003)[3] for the TT power spectrum and Kogut *et al.* (2003)[12] for the TE power spectrum. We also make available a subroutine that computes the likelihood for WMAP data given a set of C_ℓ, please refer to Verde *et al.* (2003)[8] if using this routine.

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DISCUSSION

Peter Rosen (DOE): What are the errors on the neutrino mass numbers that you gave?

Licia Verde: The number I quoted is the 95% upper limit on the neutrino mass, assuming there are 3 degenerate neutrino species. You may want to remember the value for $\Omega_\nu h^2$, which is probably more useful to you.

Chang Kee Jung (SUNY at Stony Brook): Do you see any more improvement in that number? Is there more data or any other future more precise measurement? There must be some kind of systematic limit on how well you can do with the neutrino mass.

Licia Verde: That limit can be improved in the very short term in 2 ways: first of all: better signal-to-noise. WMAP is still up there and the 2 years worth of data are "in the can" as of a few days ago. Better signal-to-noise can reduce the error bars on the other cosmological parameters this will shrink the degeneracies and help everything else.

Also, since the publication of the WMAP results, people have started analyzing gravitational lensing observations that directly probe the dark matter power spectrum at lower redshift. Basically what we are using is the fact that neutrinos stream freely so they tend to suppress or erase fluctuations on small scales. Then you compare the fluctuations on this side of the plot from the CMB (Fig. 6 on the left-hand-side) and the fluctuations on this side on the larger scale structures scales (Fig. 6 on the right-hand-side) and get a constraint from the growth of the fluctuation and the shape (see Fig. 9).

When you look at galaxies you have the uncertainties that you don't really know how to trace the mass. We have some handle on that but that grows the error bars. By looking at gravitational lensing you don't have that uncertainty. By using those data the constraint I think can be improved, but I didn't have the chance to work through the data yet.

As the data set improve and the statistical error-bars shrink, the big challenge will be to have good control of systematics. The CMB is a very "clean" data set because physics at the last scattering surface is simple and well understood. On the other hand, the physics that governs large-scale structure is connected to galaxy formation and evolution, is complicated and highly non-linear. Better understanding and modeling of the systematics induced by galaxy formation and evolution will be vital to further improve this measurement.

S. Sumowidagdo (Florida State University): Is there any chance for WMAP to observe tensor perturbation?

Licia Verde: We put some limits on tensors which we can discuss in more details in the afternoon discussion session. The polarization data will significantly improve: we will publish soon not just the power spectrum of the cross correlation between temperature and polarization but the polarization auto-correlation power spectrum and that will improve the current constraints. Having said this, a detection is in principle possible, but only for models with significant tensor modes.