Cosmological Implications of 3\textsuperscript{rd} Year WMAP Data

Cosmological implications of 3\textsuperscript{rd} year WMAP data

Consistency

How to describe the data usefully

Fits

What have WMAP collected and how to show it

Parameters

ΛCDM parameter fit using just WMAP

WMAP Data

Big Bang, Inflation, Last Scattering, Reionization, CMB structure,…

CMB Basics

Small and large scale, Supernovas, Lensing,…

CMB Basics

CMB Observations

<10^{-35}s 3 \times 10^5\text{yrs} 10^{10}\text{yrs}

Exponential Stretch

Horizon

Inflation Last Scattering Horizon Crossing

Gravitational Instability

CMB Observer

Galaxies

Large Scale Structure

Time

Rapid Expansion
CMB Basics

Small Angles

Fundamental Mode

Overtones
WMAP Data

Time Ordered Data,
Instrument corrections,
Local foregrounds: Earth, Sun,…
Order of $10^{10}$ data points.

Temperature maps,
Galactic foregrounds,
ILC of various bands,
Order of $10^6$ data points.

TT, TE Power spectrum (there is EE also)
Binning, averaging, smoothing…
Order of $10^3$ data points.
Parameters

Power spectrum can be described by **10-20 Physically meaningful parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_0$</td>
<td>$73.2^{+3.1}_{-3.2}$ km s$^{-1}$ Mpc$^{-1}$</td>
<td>Hubble parameter</td>
</tr>
<tr>
<td>$\Omega_b$</td>
<td>$0.0444^{+0.0042}_{-0.0035}$</td>
<td>Baryon density</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>$0.266^{+0.025}_{-0.040}$</td>
<td>Total matter density (baryons + dark matter)</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$0.079^{+0.029}_{-0.032}$</td>
<td>Optical depth to reionization</td>
</tr>
<tr>
<td>$A_s$</td>
<td>$0.813^{+0.042}_{-0.052}$</td>
<td>Scalar fluctuation amplitude</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.948^{+0.015}_{-0.018}$</td>
<td>Scalar spectral index</td>
</tr>
</tbody>
</table>

*Basic parameters*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_0$</td>
<td>$0.94^{+0.06}_{-0.09} \times 10^{-26}$ kg/m$^3$</td>
<td>Critical density</td>
</tr>
<tr>
<td>$\Omega_\Lambda$</td>
<td>$0.732^{+0.040}_{-0.025}$</td>
<td>Dark energy density</td>
</tr>
<tr>
<td>$z_{\text{ion}}$</td>
<td>$10.5^{+2.6}_{-2.9}$</td>
<td>Reionization red-shift</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>$0.772^{+0.036}_{-0.048}$</td>
<td>Galaxy fluctuation amplitude</td>
</tr>
<tr>
<td>$t_0$</td>
<td>$13.73^{+0.13}_{-0.17} \times 10^9$ years</td>
<td>Age of the universe</td>
</tr>
</tbody>
</table>

*Derived parameters*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w$</td>
<td>$-0.926^{+0.051}_{-0.075}$</td>
<td>Equation of state</td>
</tr>
<tr>
<td>$r$</td>
<td>$&lt; 0.55$ (2$\sigma$)</td>
<td>Tensor-to-scalar ratio</td>
</tr>
<tr>
<td>$\Omega_k$</td>
<td>$-0.010^{+0.014}_{-0.012}$</td>
<td>Spatial curvature</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$-0.102^{+0.050}_{-0.043}$</td>
<td>Running of the spectral index</td>
</tr>
<tr>
<td>$\Sigma m_\nu$</td>
<td>$&lt; 0.87$ eV (2$\sigma$)</td>
<td>Summed neutrino masses</td>
</tr>
</tbody>
</table>

Parameters are not independent but constrained depending on a model used.
### Parameters

#### Baryon Content

- $\Omega_B = 0.005$

- $\ell(l+1)C_{\ell} \text{ (Power)}$

#### Matter Density

- $\Omega_m h^2 = 0.10$

- $\ell(l+1)C_{\ell} \text{ (Power)}$

#### Curvature and Cosmological Constant

- $\Omega_0 = 1.0$

- $\ell(l+1)C_{\ell} \text{ (Power)}$

#### Reionization Optical Depth

- $\tau = 0 - 1$

- $\ell$

- Power ($\mu K^2$)

- $10^3$

- $10^2$

- $10^1$

- $10^0$

- $10^{-1}$

- $10^1$ to $10^5$

- $10^5$ to $10^9$

- Temperature, Cross, E-polar
Parameters

Sounds

Curvature

Physical Landscape
Fits and Consistency

- CMB Basics
- WMAP Data
- Parameters
- Fits
- Consistency
- Cosmology
Parameter set is chosen:

\[ p = \{ \omega_b, \omega_c, \tau, \Omega_\Lambda, w, \Omega_k, f_v, N_v, \Delta^2_R, n_s, r, dn_s/d \ln k, A_{SZ}, b_{SDSS}, z_s \}, \]

Bayesian fits are done using uniform priors for these parameters.

Physical model is chosen, Cold Dark Matter with Cosmological Constant.

Other models are compared.

Other experimental results are used to enhance and test WMAP.
Fits

$\Lambda$CDM model parameter fit using just WMAP: Power Spectrum

Fig. 2.—Comparison of the predictions of the different best-fit models to the data. The black line is the angular power spectrum predicted for the best-fit 3 year WMAP only $\Lambda$CDM model. The red line is the best fit to the 1 year WMAP data. The orange line is the best fit to the combination of the 1 year WMAP data, CBI and AcBAR (WMAPext in Spergel et al. 2003). The solid data points represent the 3 year data and the light gray data points the first-year data.
Fits

\(\Lambda\)CDM model parameter fit using just WMAP: Improvement

Fig. 1.—Improvement in parameter constraints for the power-law \(\Lambda\)CDM model (model M5 in Table 3). The contours show the 68\% and 95\% joint 2D marginalized contours for the \((\Omega_m h^2, \sigma_8)\) plane \((\text{left})\) and the \((n_s, \tau)\) plane \((\text{right})\). The black contours represent the first-year WMAP data (with no prior on \(\tau\)). The red contours show the first-year WMAP data combined with CBI and ACBAR (WMAPext in Spergel et al. 2003). The blue contours represent the three year WMAP data only with the SZ contribution set to 0 to maintain consistency with the first-year analysis. The WMAP measurements of EE power spectrum provide a strong constraint on the value of \(\tau\). The models with no reionization \((\tau = 0)\) or a scale-invariant spectrum \((n_s = 1)\) are both disfavored at \(\Delta \chi^2_{\text{eff}} > 6\) for five parameters (see Table 3). Improvements in the measurement of the amplitude of the third peak yield better constraints on \(\Omega_m h^2\).
## Fits

Is the chosen $\Lambda$CDM model the best?

**Goodness of Fit, $\Delta \chi^2_{\text{eff}} = -2 \ln \mathcal{L}$, for WMAP Data Only Relative to a Power-Law $\Lambda$CDM Model**

<table>
<thead>
<tr>
<th>Model Number</th>
<th>Model</th>
<th>$-\Delta(2 \ln \mathcal{L})$</th>
<th>$N_{\text{par}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Scale-invariant fluctuations ($n_s = 1$)</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>M2</td>
<td>No reionization ($\tau = 0$)</td>
<td>7.4</td>
<td>5</td>
</tr>
<tr>
<td>M3</td>
<td>No dark matter ($\Omega_c = 0$, $\Omega_\Lambda \neq 0$)</td>
<td>248</td>
<td>6</td>
</tr>
<tr>
<td>M4</td>
<td>No cosmological constant ($\Omega_c \neq 0$, $\Omega_\Lambda = 0$)</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>M5</td>
<td>Power law $\Lambda$CDM</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>M6</td>
<td>Quintessence ($w \neq -1$)</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>M7</td>
<td>Massive neutrino ($m_\nu &gt; 0$)</td>
<td>$-1$</td>
<td>7</td>
</tr>
<tr>
<td>M8</td>
<td>Tensor modes ($r &gt; 0$)</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>M9</td>
<td>Running spectral index ($dn_s/d \ln k \neq 0$)</td>
<td>$-4$</td>
<td>7</td>
</tr>
<tr>
<td>M10</td>
<td>Nonflat universe ($\Omega_k \neq 0$)</td>
<td>$-2$</td>
<td>7</td>
</tr>
<tr>
<td>M11</td>
<td>Running spectral index and tensor modes</td>
<td>$-4$</td>
<td>8</td>
</tr>
<tr>
<td>M12</td>
<td>Sharp cutoff</td>
<td>$-1$</td>
<td>7</td>
</tr>
<tr>
<td>M13</td>
<td>Binned $\Delta^2_R(k)$</td>
<td>$-22$</td>
<td>20</td>
</tr>
</tbody>
</table>

**Note.**—A worse fit to the data is $\Delta \chi^2_{\text{eff}} > 0$.

This is the simplest test, Bayesian testing is needed.
Consistency

Small number of parameters and models lead to degeneracy.

Observations of other physical events and on other scales helps break these.

Observations focused on other scales and events test WMAP results.

Three main groups of external data:

1) Large scale: SDSS

2) Small scale: CBI, VSA, BOOMERANG, ACBAR

3) Other physics: Supernovas, Lensing, …
Fig. 6.—Left: Predicted power spectrum (based on the range of parameters consistent with the WMAP-only parameters) is compared to the mass power spectrum inferred from the SDSS galaxy power spectrum (Tegmark et al. 2004b) as normalized by weak lensing measurements (Seljak et al. 2005b). Right: Predicted power spectrum is compared to the mass power spectrum inferred from the 2dFGRS galaxy power spectrum (Cole et al. 2005) with the best-fit value for $b_{2dFGRS}$ based on the fit to the WMAP model. Note that the 2dFGRS data points shown are correlated.
Fig. 5.—Prediction for the small-scale angular power spectrum seen by ground-based and balloon CMB experiments from the $\Lambda$CDM model fit to the WMAP data only. The colored lines show the best-fit (red) and the 68% (dark orange) and 95% confidence levels (light orange) based on fits of the $\Lambda$CDM models to the WMAP data. The points in the figure show small-scale CMB measurements (Ruhl et al. 2003; Abroe et al. 2004; Kuo et al. 2004; Readhead et al. 2004a; Dickinson et al. 2004). The plot shows that the $\Lambda$CDM model (fit to the WMAP data alone) can accurately predict the amplitude of fluctuations on the small scales measured by ground and balloon-based experiments.
Fig. 7.—Prediction for the mass fluctuations measured by the CFHTLS weak-lensing survey from the $\Lambda$CDM model fit to the WMAP data only. The blue, red, and green contours show the joint 2D marginalized 68% and 95% confidence limits in the $(\sigma_8, \Omega_m)$ plane for WMAP only, CFHTLS only and WMAP + CFHTLS, respectively, for the power-law $\Lambda$CDM models. All constraints come from assuming the same priors on input parameters, with the additional marginalization over $z_e$ in the weak lensing analysis, using a top-hat prior of $0.613 < z_e < 0.721$. While lensing data favors higher values of $\sigma_8 \simeq 0.8-1.0$ (see § 4.1.7), X-ray cluster studies favor lower values of $\sigma_8 \simeq 0.7-0.8$ (see § 4.1.9).
Consistency

Ho

Li abundance:
Theory: 2.64 +/- 0.03
WMAP: 2.3 +/- 0.1

Fig. 9.—One-dimensional marginalized distribution of $\Omega_m h^2$ for WMAP, WMAP + CBI + VSA, WMAP + BOOM + ACBAR, WMAP + SDSS, WMAP + SN(SNLS), WMAP + SN(HST/GOODS), WMAP + 2dFGRS, and WMAP + CFHTLS for the power-law $\Lambda$CDM model.
Cosmology

- CMB Basics
- WMAP Data
- Parameters
- Fits
- Consistency
- Cosmology
Fig. 14.—Joint two-dimensional marginalized contours (68% and 95% confidence levels) for inflationary parameters \((r_{0.002}, n_s)\). We assume a power-law primordial power spectrum, \(d\nu/d\ln k = 0\), as these models predict a negligible amount of running index, \(d\nu/d\ln k \approx -10^{-3}\). Upper left: WMAP only. Upper right: WMAP + SDSS. Lower left: WMAP + 2dFGRS. Lower right: WMAP + CBI + VSA. The dashed and solid lines show the range of values predicted for monomial inflaton models with 50 and 60 e-folds of inflation (eq. [13]), respectively. The open and filled circles show the predictions of \(m^2\phi^2\) and \(\lambda\phi^4\) models for 50 and 60 e-folds of inflation. The rectangle denotes the scale-invariant Harrison-Zel’dovich-Peebles (HZ) spectrum \((n_s = 1, r = 0)\). Note that the current data prefer the \(m^2\phi^2\) model over both the HZ spectrum and the \(\lambda\phi^4\) model by likelihood ratios greater than 12. \((\Delta \chi^2 > 5)\).
Cosmology Composition?

Fig. 15.—Constraints on the equation of state of dark energy, in a flat universe model based on the combination of WMAP data and other astronomical data. We assume that $w$ is independent of time and ignore density or pressure fluctuations in dark energy. In all of the figures, WMAP only constraints are shown in blue and WMAP + astronomical data set in red. The contours show the joint 2D marginalized contours (68% and 95% confidence levels) for $\Omega_m$ and $w$. Upper left: WMAP only and WMAP + SDSS. Upper right: WMAP only and WMAP + 2dFGRS. Lower left: WMAP only and WMAP + SN(HST/GOODS). Lower right: WMAP only and WMAP + SN(SNLS). In the absence of dark energy fluctuations, the excessive amount of ISW effect at $l < 10$ places significant constraints on models with $w < -1$. 
Fig. 21.—Range of nonflat cosmological models consistent with the WMAP data only. The models in the figure are all power-law CDM models with dark energy and dark matter, but without the constraint that $\Omega_m + \Omega_\Lambda = 1$ (model M10 in Table 3). The different colors correspond to values of the Hubble constant as indicated in the figure. While models with $\Omega_\Lambda = 0$ are not disfavored by the WMAP data only ($\Delta \chi^2_{\text{eff}} = 0$; model M4 in Table 3), the combination of WMAP data plus measurements of the Hubble constant strongly constrain the geometry and composition of the universe within the framework of these models. The dashed line shows an approximation to the degeneracy track: $\Omega_K = -0.3040 + 0.4067 \Omega_\Lambda$. Note that for these open universe models, we assume a flat prior on $\Omega_\Lambda$. 
3rd year WMAP data in concert with other observations and $\Lambda$CDM theory.

Significantly improved parameter precision.

Significant limits on composition and geometry of the Universe.

Issues:

$H_0$ value and Li abundance.

$\Lambda$CDM model is now very constrained: double edged sword?

Other models are very undeveloped: fair comparison?