Results from WMAP

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The peaks in the power spectra correspond to harmonics of the universe.

- Fully compressed (half cycle)
- Compressed, then rarified (full cycle)
- Maximum velocity, minimum density fluctuation

**Graph:**
- Full sky
- 1 degree
- Small scales

**Axes:**
- Multipole moment $l$
- $l(l+1)C_l^{TT}/2\pi [\mu K^2]$
WMAP views the decoupling surface

Ratio of heights of 1st and 2nd peaks gives baryon density:

$$\Omega_b h^2 = 0.02267^{+0.00058}_{-0.00059}$$

Baryon density determines:

$$t_{\text{decoupling}} = 376,971^{+3162}_{-3167} \text{ years}$$

$$z_{\text{decoupling}} = 1090.88 \pm 0.72$$

$$r_s = \frac{c_s t_{\text{decoupling}}}{1 + z}$$

$$r_s = 145.9^{+1.1}_{-1.2} \text{ Mpc}$$

Assume flatness, get:

$$H_0 = 70.5 \pm 1.3 \frac{\text{km/s}}{\text{Mpc}}$$

Assume $H_0$ from HST, get flatness:

$$\Omega_{\text{tot}} = 1.0050^{+0.0060}_{-0.0061}$$
WMAP measures the contents of the universe

380,000 years after big bang

Today, 13.72 +/- 0.12 Gyr
Big Bang
Nucleosynthesis

$^4$He mass fraction from extragalactic HII regions

Width of curve is 1-sigma error in prediction

Cyburt,

WMAP 5yr data added in brown

Fields & Olive, 1998
Izotov & Thuan, 1998
WMAP constrains inflation through the primordial power spectrum

\[
\Delta^2_R(k) \equiv \frac{k^3 P_R(k)}{2\pi^2} = \Delta^2_R(k_0) \left( \frac{k}{k_0} \right)^{n_s(k_0) - 1 + \frac{1}{2} \frac{dn_s}{d\ln k} \ln \left( \frac{k}{k_0} \right)}
\]

There is no evidence for the running spectral index:

\[
n_s = 0.960 \pm 0.013, \quad \frac{dn_s}{d\ln k} = 0
\]

\[
n_s = 1.017^{+0.042}_{-0.043}, \quad \frac{dn_s}{d\ln k} = -0.028 \pm 0.020
\]
WMAP constrains inflation through the tensor to scalar ratio: gravity waves

$r < 0.22$ (95% CL)

Komatsu et al., 2009
Some inflationary models are being ruled out

Komatsu et al, 2009
Inflation predicts a high degree of Gaussianity

\[ p(x) = \frac{1}{\sqrt{|2\pi C|}} \exp \left( -\frac{1}{2} (x - \bar{x})^T C^{-1} (x - \bar{x}) \right) \]

where \( x \) is a column vector of fourier modes, pixel values, or alm coefficients

This is frequently tested by:
1. generating many random realizations of the CMB,
2. adding realistic noise, and
3. comparing the value of some statistic on the CMB to the random realizations
The 1-point functions of the CMB are Gaussian.

41 GHz

61 GHz

94 GHz

Spergel et al., 2007
The right hand column is consistent with zero

Number of islands minus number of lakes

Length of shoreline

Area below sea level

Komatsu et al., 2009
The $f_{\text{NL}}$ parameter is also constrained by WMAP data

\[ \Phi = \Phi_L + f_{\text{local}}^2 \Phi_L \]

\[ \Phi \approx 10^{-5} \]

\[ -9 < f_{\text{local}} < 111 \text{ (95\% CL)} \]

\[ -151 < f_{\text{equil}} < 253 \text{ (95\% CL)} \]

If the CMB were significantly non-Gaussian, it would be a problem for single field slow-roll inflation
WMAP detects no isocurvature modes
uncorrelated with adiabatic modes

anti-correlated with adiabatic modes

\[ \alpha_0, \alpha_{-1}, \Omega_m h^2, n_s \]

Komatsu et al., 2009
WMAP finds no evidence for parity violation: No rotation in linear polarization of photons

Photon rotation will change a TE correlation into a TB correlation

Gravitational lensing will turn E modes into B modes, but it won’t create a TB correlation
WMAP finds no evidence for parity violation: No rotation in linear polarization of photons

Limits on rotation since last scattering
Limits on rotation since reionization

TB spectrum, consistent with zero

Nolta, et al., 2009

Komatsu, et al., 2009
WMAP constrains the number of relativistic degrees of freedom, $N_{\text{eff}}$, for $z \sim 1000-3000$

WMAP prefers a light relativistic particle that couples very weakly to baryons: neutrinos

Dunkley et al, 2009
\( \Delta \chi^2 = \Delta ( -2 \ln L ) = -8.2 \)
WMAP+BAO+SN constrain the neutrino mass

\[ \sum m_\nu < 0.67 \text{ eV} \ (95\% \text{ CL}) \]

An independent measurement of sigma8 would help
We have a well-supported standard model of cosmology:
   Nucleosynthesis
   Hubble expansion
   CMB existence & blackbody spectrum
   Simple 6-parameter model fits CMB spectra

Inflation is being tested/probed:
   The universe is flat
   $n_s$ is significantly and slightly $< 1$
   $dn_s/d \ln k \sim 0$
   CMB fluctuations appear Gaussian
   Isocurvature modes are not detected

No evidence for parity violation
Preference for neutrinos

Questions?
WMAP constrains inflation through the tensor to scalar ratio: gravity waves

Keeping all other parameters ($n_s$) fixed:
- low l polarization: $r < 20$
- + high l polarization (TE): $r < 2$
- + low l temperature (TT): $r < 0.2$

Komatsu et al., 2009