Cosmology from 3 years of WMAP

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What is WMAP?

- Satellite detecting primordial photons “cosmic microwave background”
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The oldest fossil from the early universe

- Inflation and Grand Unification?
- Nucleosynthesis
- Quantum Gravity/ Trans-Planckian effects...
- Testable in particle accelerators
- Imprint in CMB
Inflation and Grand Unification?

Quantum Gravity/Trans-Planckian effects...

Galaxy formation

Reionization

Nucleosynthesis

Recombination

Dark Energy domination

Imprint on CMB

Testable in particle accelerators

Imprint in CMB

The cosmic equivalent of tree rings...

CMB

Inflation and Grand Unification?

Quantum Gravity/Trans-Planckian effects....
Important comparisons with later observations

- Dark Energy domination
- Reionization
- Galaxy formation
- Recombination
- Nucleosynthesis
- Supernovae
- Weak lensing
- LSS surveys
- Imprint on CMB

Testable in particle accelerators

- Inflation and Grand Unification?
- Quantum Gravity/ Trans-Planckian effects....
Cosmological discovery is an iterative process...

Pure theory
(and conjecture)

Detailed modeling of consequences and real life contaminants

Precision surveys to check theoretical predictions
Maps and galactic foregrounds

Raw

Temperature (~10s uK)

Polarization (~0.1s uK)

FG

Cleaned
Temperature & polarization patterns correlated

Polarization created by Thomson scattering of photons with quadrupole distribution

- Radial polarization pattern around cold spots
- Matter flows into high density region
- Tangential polarization pattern around hot spots
- Low density regions which matter flows out of

Generates curl free polarization pattern - ‘E’ mode polarization

E-mode (curl free)  B-mode (div free)
Summary of power spectrum results

Reionization bump

BB upper limit
A simple cosmological model with only 6 parameters fits the WMAP data:
\[ \{ \Omega_b h^2, \Omega_m h^2, h, \tau, n_s, A_s \} \Rightarrow \chi^2/dof = 1.04 \]

Summary:

- Run model forward in time
  - predict cosmological evolution

- Go backwards in time
  - to study early universe

- Constrain variants on simplest model
  - open universe,
  - massive neutrinos
  - Dark energy models
  - Beyond power law inflation
Analysis of Polarization Reionization Signature

- Reionization signature statistically significant, even with just polarization data
  \[ \tau = 0 \Rightarrow \Delta \chi^2_{\text{eff}} = +8 \text{ vs } \text{bestfit } \tau > 0 \]
- More years of data will yield more insights into reionization e.g. 2 step process?
  - \( x_e = 1 \) for \( z < 7 \)
  - \( x_e = x_e^0 \) for \( 7 < z < z_{\text{rei}} \)
  \[ \Rightarrow 0.057 < \tau < 0.17 \text{ (1}\sigma) \]
Improvement in Parameters driven by polarization measurement of reionization ($\tau$)

Comparison of 1st year and 3rd year WMAP constraints

- WMAP yr 1
- WMAP yr 1 + other CMB
- WMAP 3 yr
- $\Omega_m h^2$
ΛCDM: WMAP and WMAP+other data
WMAP fits predict small scale CMB

Predicted small scale CMB spectrum from WMAP alone
WMAP fits predict $H(z)$

Predicted $H(z)$ evolution

Synthetic stellar pop
Ages of galaxies
(Simon et al '05)

Luminosity distance prediction from WMAP alone

SNLS

HST/GOODS
WMAP fits predict galaxy and mass distribution

Predicted $P(k)$ for SDSS and 2dF galaxy surveys from WMAP alone

$P(k) \left[ (\text{h/Mpc})^3 \right]$ vs $k (\text{h/Mpc})$
WMAP fits predict primordial abundances

(Steigman et al 2005)

<table>
<thead>
<tr>
<th>(10^5y_D^{FF} )</th>
<th>CMB-based BBN prediction</th>
<th>Observed Value</th>
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</thead>
<tbody>
<tr>
<td>(10^5y_D )</td>
<td>2.58^{+0.14}_{-0.13}</td>
<td>1.6 - 4.0</td>
</tr>
<tr>
<td>(Y_P )</td>
<td>1.05 ± 0.03 ± 0.03 (syst.)</td>
<td>&lt; 1.1 ± 0.2</td>
</tr>
<tr>
<td>([\text{Li}])</td>
<td>0.24815 ± 0.00033 ± 0.0006(syst.)</td>
<td>0.232 - 0.258</td>
</tr>
<tr>
<td></td>
<td>2.64 ± 0.03</td>
<td>2.2 - 2.4</td>
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</table>
Predictions of inflation

- Acceleration induced by slow roll down scalar potential
  - Near scale invariant tilt
  - Small but non-zero tensor contribution $r = T/S$

- Acceleration causes Hubble horizon decreases
  - Flatness is an attractor
  - Density fluctuations seeded by Gaussian quantum fluctuations

\[ \eta = \frac{m_p^2 V''}{8\pi V} \ll 1 \]
\[ \varepsilon = \frac{m_p^2 V'^2}{16\pi V^2} \ll 1 \]
\[ n_s = 1 - 6\varepsilon + 2\eta \]
Looking Pretty Gaussian....

One point distribution function
(Npix = 3072, 12288, 786432)

Still some interesting large scale correlations...
Constraints on power law initial $P(k) \propto k^{n-1}$ + tensors, $r = A_T/A_S$

- WMAP
- WMAP + SDSS
- WMAP + 2dF
- WMAP + CBI+VSA

$n_s(k=0.002/\text{Mpc})$
Alternative power spectrum models

Sharp k cutoff in initial spectrum

\[ \Delta \chi^2_{\text{eff}} = -1 \]

Improvement in fit by suppressing large scale power small,

\[ \Delta \chi^2_{\text{eff}} = -22 \]

\[ P(k) = 0, \ k < k_c \]

\[ k_c [10^{-4} \text{ Mpc}^{-1}] \]

Reconstruction of P(k) in 15 k bins

P(k) reconstruction consistent with power law P(k)
‘Bumps and wiggles’ reduced

Based on model by Martin and Ringeval (2003)

Other pure $\cos(k)$ and $\cos(\log k)$ modulations produce similar improvements: $\Delta \chi^2_{\text{eff(ALL)}} = -5$ and $-9.5$ for 2 extra parameters
Geometry of the universe

<table>
<thead>
<tr>
<th>Data Set</th>
<th>$\Omega_K$</th>
<th>$\Omega_\Lambda$</th>
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<tbody>
<tr>
<td>WMAP + h = 0.72 ± 0.08</td>
<td>-0.003$^{+0.013}_{-0.017}$</td>
<td>0.758$^{+0.035}_{-0.058}$</td>
</tr>
<tr>
<td>WMAP + SDSS</td>
<td>-0.037$^{+0.022}_{-0.014}$</td>
<td>0.650$^{+0.058}_{-0.045}$</td>
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<tr>
<td>WMAP + 2dFGRS</td>
<td>-0.0057$^{+0.00085}_{-0.00064}$</td>
<td>0.739 ± 0.028</td>
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<tr>
<td>WMAP + SDSS LRG</td>
<td>-0.008$^{+0.011}_{-0.015}$</td>
<td>0.729$^{+0.021}_{-0.026}$</td>
</tr>
<tr>
<td>WMAP + SNLS</td>
<td>-0.015$^{+0.016}_{-0.016}$</td>
<td>0.719$^{+0.023}_{-0.028}$</td>
</tr>
<tr>
<td>WMAP + SNGold</td>
<td>-0.017$^{+0.020}_{-0.019}$</td>
<td>0.703$^{+0.036}_{-0.032}$</td>
</tr>
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</table>

WMAP only

No CDM $\Delta \chi^2_{\text{eff}} = +248$
No $\Lambda$ $\Delta \chi^2_{\text{eff}} = 0$  ($H_0 \sim 30$)
### Massive neutrinos

**$\Sigma m_v$ (eV) 95% CL**

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<tr>
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<th>$\Sigma m_v$ (eV)</th>
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<tr>
<td>WMAP only</td>
<td>2.0</td>
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<tr>
<td>WMAP+SDSS</td>
<td>0.93</td>
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<tr>
<td>WMAP+2dF</td>
<td>0.90</td>
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<tr>
<td>CMB +LSS + SN</td>
<td>0.68</td>
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![Graph showing $\sigma_8$ and $\Sigma m_v$ (eV) relationships](image)
Dark Energy

Clustering dark energy $c_s^2 = 1$ $w \neq -1$

If fluctuations in DE negligible

Sensitive to assumptions about clustering properties of Dark Energy
Robustness of dark energy constraints....

$w + \text{curvature}$

$CMB + SN + LSS$

$\Omega_k$

$w$

$\Sigma m_v (eV)$

$w + \text{massive neutrinos}$

$CMB + SN + LSS$
Beyond WMAP: Applying WMAP to new tasks

- Cross-correlation with structure:
  - Exciting opportunities to probe dark energy, reionization ...

- Complementary cosmological experiments
  - Crucial complementary parameter constraints from precise understanding of physics at last scattering

- Future CMB experiments:
  - Mapping the foregrounds
  - Calibration
Small scale CMB / SZ surveys

Implications for dark matter/ dark energy research

- **Ground based e.g.**:
  - SZA ~100 clusters, 12 sqdeg, z~1, 2004
  - APEX ~1000, 200sqdeg, 2005
  - ACT ~1000 clusters, 100 sqdeg, z~1.4, early 2006, photometric support from SALT
  - SPT ~10,000 clusters, 4,000 sqdeg, z~1.2, 2007, photometric support from DES

- **Satellite**:
  - Planck, ~ 15,000 clusters, z~1, 2007

- And others ...
CMB polarization large and small scale: Primordial gravity waves & CMB lensing...

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<th>Experiment</th>
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<tr>
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<td>Observing</td>
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<tr>
<td>WMAP</td>
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<tr>
<td>DASI</td>
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<td>CBI</td>
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<td>QUAD</td>
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<tr>
<td>Amiba</td>
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<td>Clover</td>
<td>Ground</td>
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Conclusions

- WMAP now has full sky temperature and polarization maps
  - Polarization reionization signature broke cosmological degeneracies
  - Simple cosmological model has survived its most rigorous test
  - Data favors red spectral index (consistent with simple inflationary models) over Harrison-Zeldovich Peebles spectrum

- Rich prospects from combining/ correlating WMAP with complementary data

- Future CMB experiments promise insights into dark matter/dark energy and evidence of gravity wave signature from inflation