The 5-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation

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WMAP at Lagrange 2 (L2) Point

June 2001: WMAP launched!

February 2003: The first-year data release

March 2006: The three-year data release

March 2008: The five-year data release

- L2 is a million miles from Earth
- WMAP leaves Earth, Moon, and Sun behind it to avoid radiation from them
WMAP Measures Microwaves From the Universe

- The mean temperature of photons in the Universe today is 2.725 K (+/- 0.001 K)
- WMAP is capable of measuring the temperature contrast down to better than one part in millionth
Journey Backwards in Time

- The Cosmic Microwave Background (CMB) is the fossil light from the Big Bang.
- This is the oldest light that one can ever hope to measure.
- CMB is a direct image of the Universe when the Universe was only 380,000 years old.

- CMB photons, after released from the cosmic plasma “soup,” traveled for 13.7 billion years to reach us.
- CMB collects information about the Universe as it travels through it.
The Wilkinson Microwave Anisotropy Probe (WMAP)

• A microwave satellite working at L2
• Five frequency bands
  – K (22GHz), Ka (33GHz), Q (41GHz), V (61GHz), W (94GHz)
  – Multi-frequency is crucial for cleaning the Galactic emission

• The Key Feature: Differential Measurement
  – The technique inherited from COBE
  – 10 “Differencing Assemblies” (DAs)
  – K1, Ka1, Q1, Q2, V1, V2, W1, W2, W3, & W4, each consisting of two radiometers that are sensitive to orthogonal linear polarization modes.

• Temperature anisotropy is measured by single difference.
• Polarization anisotropy is measured by double difference.
WMAP can measure polarization as well!
**WMAP Spacecraft**

**Radiative Cooling: No Cryogenic System**

- **60K**
  - line of sight
  - back to back Gregorian optics, 1.4 x 1.6 m primaries

- **90K**
  - focal plane assembly
  - feed horns
  - secondary reflectors

- **300K**
  - thermally isolated instrument cylinder

- **Warm spacecraft with:**
  - instrument electronics
  - attitude control/propulsion
  - command/data handling
  - battery and power control

- **Deployed solar array w/ web shielding**

- **Upper omni antenna**

- **Passive thermal radiator**
WMAP on google.com/sky
WMAP 5-Year Papers

- Hinshaw et al., “Data Processing, Sky Maps, and Basic Results” 0803.0732
- Hill et al., “Beam Maps and Window Functions” 0803.0570
- Gold et al., “Galactic Foreground Emission” 0803.0715
- Wright et al., “Source Catalogue” 0803.0577
- Nolta et al., “Angular Power Spectra” 0803.0593
- Dunkley et al., “Likelihoods and Parameters from the WMAP data” 0803.0586
- Komatsu et al., “Cosmological Interpretation” 0803.0547
WMAP 5-Year Science Team

- C.L. Bennett
- G. Hinshaw
- N. Jarosik
- S.S. Meyer
- L. Page
- D.N. Spergel
- E.L. Wright
- M.R. Greason
- M. Halpern
- R.S. Hill
- A. Kogut
- M. Limon
- N. Odegard
- G.S. Tucker
- J. L. Weiland
- E. Wollack
- J. Dunkley
- B. Gold
- E. Komatsu
- D. Larson
- M.R. Nolta

Special Thanks to WMAP Graduates!

- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- L. Verde
WMAP: Selected Results From the Previous Releases

- **2003: The first-year results**
- Age of the Universe: **13.7 (+/- 0.2)** billion years
- “Cosmic Pie Chart”
  - Atoms (baryons): **4.4 (+/- 0.4)** %
  - Dark Matter: **23 (+/- 4)** %
  - Dark Energy: **73 (+/- 4)** %
  - Erased lingering doubts about the existence of DE
- “Breakthrough of the Year #1” by Science Magazine
WMAP: Selected Results

From the Previous Releases

- **2006: The three-year results**

- **Polarization** of the cosmic microwave background measured with the unprecedented accuracy
  - The epoch of the formation of first stars (onset of the “cosmic reionization”)
  - ~400 million years after the Big Bang

- Evidence for a scale dependence of the amplitude of primordial fluctuations (the so-called “tilt”)
  - Peering into the cosmic inflation (ultra early univ!)
Universe today

- **Age:** $13.73 \pm 0.12$ Gyr
- **Atoms:** $4.62 \pm 0.15\%$
- **Dark Matter:** $23.3 \pm 1.3\%$
- **Vacuum Energy:** $72.1 \pm 1.5\%$

When CMB was released 13.7 B yrs ago

- A significant contribution from the *cosmic neutrino background*
How Did We Use This Map?

WMAP 5-year

-200 T(μK) +200
The Spectral Analysis

Much improved measurement of the 3rd peak!

Cosmic variance limited to $l=530$
The Cosmic Sound Wave

Angular Power Spectrum

$\ell (\ell + 1) C_\ell / 2\pi$ [$\mu$K$^2$]

Note consistency around the 3rd-peak region

Multipole moment $\ell$

WMAP 5yr  
Acbar  
Boomerang  
CBI
The Cosmic Sound Wave

- We measure the composition of the Universe by analyzing the waveform of the cosmic sound waves.
How About Polarization?

- Polarization is a rank-2 tensor field.
- One can decompose it into a divergence-like “E-mode” and a vorticity-like “B-mode”.

Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky, Stebbins (1997)
5-Year E-Mode Polarization Power Spectrum

Errors include cosmic variance

Symbols are upper limits

$\ell(\ell+1)C_{\ell}^{EE}/2\pi$ [$\mu$K$^2$]

Multipole moment $\ell$
Measuring The Optical Depth of the Universe

- Optical Depth measured from the E-mode power spectrum:
  - $\tau(5\text{yr}) = 0.087 \pm 0.017$
  - $\tau(3\text{yr}) = 0.089 \pm 0.030$ (Page et al.; QV only)
- 3-sigma improved to 5-sigma!
- Tau form the null map (Ka-QV) is consistent with zero

$\text{Hinshaw et al.}$
Assuming an instantaneous reionization from $x_e=0$ to $x_e=1$ at $z_{\text{reion}}$, we find $z_{\text{reion}}=11.0 \pm 1.4$ (68% CL).

The reionization was not an instantaneous process at $z\sim6$. (The 3-sigma lower bound is $z_{\text{reion}}>6.7$.)
Tilting = Primordial Shape

\[ l(l+1)C_l^{TT}/2\pi \, [\mu K^2] \]

Multipole moment \( l \)
“Red” Spectrum: $n_s < 1$
“Blue” Spectrum: $n_s > 1$

\[ l(l+1)C_l^{TT}/2\pi \text{ [\mu K}^2] \]

Multipole moment $l$
With the 5-year determination of the optical depth (tau), the most dominant source of degeneracy is now $\Omega_b h^2$, rather than tau.

- WMAP-alone: $n_s=0.963 \pm 0.014$ (Dunkley et al.)
- 2.5-sigma away from $n_s=1$
Cosmic Neutrino Background

• How do neutrinos affect the CMB?
  
  • Neutrinos add to the radiation energy density, which delays the epoch at which the Universe became matter-dominated. The larger the number of neutrino species is, the later the matter-radiation equality, $z_{\text{equality}}$, becomes.
  
  • This effect can be mimicked by lower matter density.
  
  • Neutrino perturbations affect metric perturbations as well as the photon-baryon plasma, through which CMB anisotropy is affected.
CNB As Seen By WMAP

- Multiplicative phase shift is due to the change in $z_{\text{equality}}$
  - Degenerate with $\Omega_m h^2$
- Suppression is due to neutrino perturbations
  - Degenerate with $n_s$
- Additive phase shift is due to neutrino perturbations
  - No degeneracy

$\Delta \chi^2 = 8.2 \rightarrow 99.5\% \text{ CL}$

Red: $N_{\text{eff}} = 3.04$
Blue: $N_{\text{eff}} = 0$

(Bashinsky & Seljak 2004)
• The number of neutrino species is massively degenerate with $\Omega_m h^2$, which simply traces $z_{\text{equality}}=\text{constant}$.

• But, the contours close near $N_{\text{eff}} \sim 1$, in contradiction to the prediction from $z_{\text{equality}}=\text{constant}$.
Cosmic/Laboratory Consistency

- From WMAP+BAO+SN (I will explain what BAO and SN are shortly)
  - $N_{\text{eff}} = 4.4 \pm 1.5$
- From the Big Bang Nucleosynthesis
  - $N_{\text{eff}} = 2.5 \pm 0.4$
- From the decay width of Z bosons measured in LEP
  - $N_{\text{neutrino}} = 2.984 \pm 0.008$
Testing Cosmic Inflation

~5 Tests~

• Is the observable universe flat?
• Are the primordial fluctuations adiabatic?
• Are the primordial fluctuations nearly Gaussian?
• Is the power spectrum nearly scale invariant?
• Is the amplitude of gravitational waves reasonable?
CMB to Cosmology to Inflation

- Constraints on Inflation Models
  - Gravitational waves
  - Large-angle Polarization
  - Temperature-polarization correlation (TE)
  - Radiation-matter Adiabaticity
  - Overall Tilt
  - Peak Locations
  - Distance to the LSS
  - Age of the Univ.
  - Hubble Param.
  - Dark Matter Density
  - Baryon Density
  - Baryon/Photon Density Ratio
  - Matter/Radiation Density Ratio
  - 3-d Geometry
  - Primordial Power Spectrum
  - Optical Depth
  - Break DEG.
  - Low Multipoles (ISW)
  - DEG.
How Do We Test Inflation?

• The WMAP data alone can put tight limits on most of the items in the check list. (For the WMAP-only limits, see Dunkley et al.)

• However, we can improve the limits on many of these items by adding the extra information from the distance measurements:

  • *Luminosity Distances* from Type Ia Supernovae (SN)
  
  • *Angular Diameter Distances* from the Baryon Acoustic Oscillations (BAO) in the distribution of galaxies
• WMAP measures the angular diameter distance to the decoupling epoch at $z=1090$.

• The distance depends on curvature AND other things, like the energy content; thus, we need more than one distance indicators, in order to constrain, e.g., $\Omega_m$ and $H_0$. 

Komatsu et al. 35
Type Ia Supernova (SN) Data

From these measurements, we get the **relative** luminosity distances between Type Ia SNe. Since we marginalize over the absolute magnitude, the current SN data are **not** sensitive to the absolute distances.

- Riess et al. (2004; 2006) HST data
- Astier et al. (2006) Supernova Legacy Survey (SNLS)
- Wood-Vasey et al. (2007) ESSENCE data
• BAO measured from SDSS (main samples and LRGs) and 2dFGRS (Percival et al. 2007)

• Just like the acoustic oscillations in CMB, the galaxy BAOs can be used to measure the **absolute** distances
As a result..

- $-0.0181 < \Omega_k < 0.0071$ (95% CL) for $w=-1$

- The constraint driven mostly by WMAP+BAO

- BAOs are more powerful than SNe in pinning down curvature, as they are **absolute** distance indicators.
What If Dark Energy Was Not Vacuum Energy ($w = -1$)...

- WMAP+BAO -> Curvature; WMAP+SN -> $w$
- WMAP+BAO+SN -> Simultaneous limit
- $-0.0175 < \Omega_k < 0.0085$; $-0.11 < 1 + w < 0.14$ (95% CL)
Fun Numbers to Quote

- The curvature radius of the universe is given, by definition, by
  \[ R_{\text{curv}} = \frac{3h^{-1}\text{Gpc}}{\sqrt{\Omega_k}} \]
- For negatively curved space \((\Omega_k>0)\): \(R>33h^{-1}\text{Gpc}\)
- For positively curved space \((\Omega_k<0)\): \(R>23h^{-1}\text{Gpc}\)
- The particle horizon today is \(9.7h^{-1}\text{Gpc}\)
- The observable universe is pretty flat! (Fun to teach this in class)
Implications for Inflation?

- Details aside...
  - Q. How long should inflation have lasted to explain the observed flatness of the universe?
  - A. $N_{\text{total}} > 36 + \ln(T_{\text{reheating}}/1 \text{ TeV})$
  - A factor of 10 improvement in $\Omega_k$ will raise this lower limit by 1.2.
  - Lower if the reheating temperature was $< 1 \text{ TeV}$
  - This is the check list #1
Check List #2: Adiabaticity

• The adiabatic relation between radiation and matter:
  
  \[ 3\frac{\delta \rho_{\text{radiation}}}{4\rho_{\text{radiation}}} = \frac{\delta \rho_{\text{matter}}}{\rho_{\text{matter}}} \]

• Deviation from adiabaticity: A simple-minded quantification

  • Fractional deviation of A from B = \( \frac{(A - B)}{(A + B)/2} \)
  
  \[ \delta_{\text{adi}} = \frac{[3\frac{\delta \rho_{\text{radiation}}}{4\rho_{\text{radiation}}} - \frac{\delta \rho_{\text{matter}}}{\rho_{\text{matter}}}]/}{\{[3\frac{\delta \rho_{\text{radiation}}}{4\rho_{\text{radiation}}} + \frac{\delta \rho_{\text{matter}}}{\rho_{\text{matter}}}]/2\}} \]

• Call this the “adiabaticity deviation parameter”

  • “Radiation and matter obey the adiabatic relation to (100\(\delta_{\text{adi}}\))% level.”
The negative TE at \( l \sim 100 \) is the distinctive signature of super-horizon adiabatic perturbations (Spergel & Zaldarriaga 1997).

Non-adiabatic perturbations would fill in the trough, and shift the zeros.
Axion Dark Matter?

- CMB and axion-type dark matter are adiabatic to 8.6%.
- This puts a severe limit on axions being the dominant dark matter candidate.
Check list #3: Gaussianity

- In the simplest model of inflation, the distribution of primordial fluctuations is close to a Gaussian with random phases.

- The level of non-Gaussianity predicted by the simplest model is well below the current detection limit.

- A convincing detection of primordial non-Gaussianity will rule out most of inflation models in the literature.
Angular Bispectrum

- Non-zero bispectrum means the detection of non-Gaussianity. **It’s always easy to look for deviations from zero!**
- There are many triangles to look for, but...
  - Will focus on two classes
    - “Squeezed” parameterized by $f_{NL}^{\text{local}}$
    - “Equilateral” parameterized by $f_{NL}^{\text{equil}}$
No Detection at >95%CL

-9 < $f_{\text{NL}}^{\text{(local)}}$ < 111 (95% CL)  
-151 < $f_{\text{NL}}^{\text{(equilateral)}}$ < 253 (95% CL)

These numbers mean that the primordial curvature perturbations are Gaussian to 0.1% level.

This result provides the strongest evidence for quantum origin of primordial fluctuations during inflation.
Check List #4: Scale Invariance

- For a power-law power spectrum (no $dn_s/d\ln k$):
  - WMAP-only: $n_s=0.963 \pm 0.014\pm 0.015$
  - WMAP+BAO+SN: $n_s=0.960 \pm 0.014\pm 0.013$

- 2.9 sigma away from $n_s=1$

- No dramatic improvement from the WMAP-only result because neither BAO nor SN is sensitive to $\Omega_b h^2$
Check List #5: Gravitational Waves

• How do WMAP data constrain the amplitude of primordial gravitational waves?
If all the other parameters \( (n_s \text{ in particular}) \) are fixed...

- Low-\( l \) polarization gives \( r < 20 \) (95\% CL)
- + high-\( l \) polarization gives \( r < 2 \) (95\% CL)
- + low-\( l \) temperature gives \( r < 0.2 \) (95\% CL)
• Since the limit on $r$ relies on the low-\(l\) temperature, it is strongly degenerate with $n_s$.

• The degeneracy can be broken partially by BAO&SN

• $r<0.43$ (WMAP-only) $\rightarrow$ $r<0.20$ (WMAP+BAO+SN)
$n_s > 1.0$ is Disfavored, Regardless of $r$

- The maximum $n_s$ we find at 95% CL is $n_s = 1.005$ for $r = 0.16$. 
Lowering a “Limbo Bar”

- $\lambda \varphi^4$ is totally out. (unless you invoke, e.g., non-minimal coupling, to suppress $r$...)
- $m^2\varphi^2$ is within 95% CL.
  - Future WMAP data would be able to push it to outside of 95% CL, if $m^2\varphi^2$ is not the right model.
- N-flation $m^2\varphi^2$ (Easther&McAllister) is being pushed out
- PL inflation $[a(t) \sim t^p]$ with $p<60$ is out.
- A blue index ($n_s>1$) region of hybrid inflation is disfavored
Grading Inflation

- **Flatness**: $-0.0175 < \Omega_k < 0.0085$ (not assuming $w=-1$!)
- **Non-adiabaticity**: <8.6% (axion DM); <2.0% (curvaton DM)
- **Non-Gaussianity**: $-9 < \text{Local} < 111$; $-151 < \text{Equilateral} < 253$
- **Tilt** (for $r=0$): $n_s=0.960 \pm 0.014 \pm 0.013$ [68% CL]
- **Running** (for $r=0$): $-0.0728 < \frac{dn_s}{d\ln k} < 0.0087$
- **Gravitational waves**: $r < 0.20$
  - $n_s=0.968 \pm 0.015$ [68% CL]
  - $n_s>1$ disfavored at 95% CL regardless of $r$
What else in the interpretation paper...

• Basically, we tried everything we could do (*in time before the release*) to find deviations from the simple 6-parameter $\Lambda$CDM.

• We failed to find any. A flat $\Lambda$CDM is annoying, but it is a good fit to the data!

• The interpretation paper is a journal on the pains-taking quest to look for new physics in the WMAP data. While we failed to find any, we report on quantitative, stringent limits on the deviations from the simple $\Lambda$CDM.
Dark Energy From Distance Information Alone

- We provide a set of “WMAP distance priors” for testing various dark energy models.
  - Redshift of decoupling, $z^* = 1090.04$ (Err=0.93)
  - Acoustic scale, $l_A = \pi d_A(z^*)/r_s(z^*) = 302.10$ (Err=0.86)
  - Shift parameter, $R = \sqrt{\Omega_m H_0^2} d_A(z^*) = 1.710$ (Err=0.019)
- Correlations between these three quantities are also provided.
- Top
  - Full WMAP Data
- Bottom
  - WMAP Distance Priors
Application:
\[ w(z) = w_0 + w'z/(1+z) \]

- Dark energy is pretty consistent with cosmological constant: \( w_0 = -1.09 \pm 0.12 \) & \( w' = 0.52 \pm 0.46 \) (68% CL)
• Parity violating interactions that rotate the polarization angle of CMB can produce TB and EB correlations.
These are simpler relations when there was no primordial B-mode polarization.

• How much rotation would WMAP allow?
Δα = (-1.7 +/- 2.1) degrees (68% CL)

Comparable to the astrophysical constraint from quasars and radio galaxies

Δα = (-0.6 +/- 1.5) degrees (68% CL) (Carroll 1998)

But, note the difference in path length!
• BAO helps determine the neutrino mass by giving $H_0$.

• **$\text{Sum}(m_\nu) < 0.61 \text{ eV}$ (95% CL)** -- independent of the normalization of the large scale structure.
After the Quest in Dark Forest...

...here is a report, captain...

**TABLE 2**

**Summary of the 95% confidence limits on deviations from the simple (flat, Gaussian, adiabatic, power-law) ΛCDM model.**

<table>
<thead>
<tr>
<th>Section</th>
<th>Name</th>
<th>Type</th>
<th>WMAP 5-year</th>
<th>WMAP+BAO+SN</th>
</tr>
</thead>
<tbody>
<tr>
<td>§ 3.2</td>
<td>Gravitational Wave&lt;sup&gt;a&lt;/sup&gt;</td>
<td>No Running Ind.</td>
<td>$r &lt; 0.43&lt;sup&gt;b&lt;/sup&gt;$</td>
<td>$r &lt; 0.20$</td>
</tr>
<tr>
<td>§ 3.1.3</td>
<td>Running Index</td>
<td>No Grav. Wave</td>
<td>$-0.090 &lt; dn_s/d ln k &lt; 0.019&lt;sup&gt;c&lt;/sup&gt;$</td>
<td>$-0.0728 &lt; dn_s/d ln k &lt; 0.0087$</td>
</tr>
<tr>
<td>§ 3.4</td>
<td>Curvature&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curvature Radius&lt;sup&gt;g&lt;/sup&gt;</td>
<td>Positive Curv.</td>
<td>$R_{curv} &gt; 12 \ h^{-1}\text{Gpc}$</td>
<td>$R_{curv} &gt; 23 \ h^{-1}\text{Gpc}$</td>
<td></td>
</tr>
<tr>
<td>Negative Curv.</td>
<td>$R_{curv} &gt; 23 \ h^{-1}\text{Gpc}$</td>
<td>$R_{curv} &gt; 33 \ h^{-1}\text{Gpc}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>§ 3.5</td>
<td>Gaussianity</td>
<td>Local</td>
<td>$-9 &lt; f_{NL}^{local} &lt; 111&lt;sup&gt;h&lt;/sup&gt;$</td>
<td>N/A</td>
</tr>
<tr>
<td>§ 3.6</td>
<td>Adiabaticity</td>
<td>Equilateral</td>
<td>$-151 &lt; f_{NL}^{equil} &lt; 253&lt;sup&gt;i&lt;/sup&gt;$</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axion</td>
<td>$\alpha_0 &lt; 0.16&lt;sup&gt;j&lt;/sup&gt;$</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Curvaton</td>
<td>$\alpha_{-1} &lt; 0.011&lt;sup&gt;k&lt;/sup&gt;$</td>
<td>$\alpha_0 &lt; 0.067&lt;sup&gt;k&lt;/sup&gt;$</td>
</tr>
<tr>
<td>§ 4</td>
<td>Parity Violation</td>
<td>Chern-Simons&lt;sup&gt;n&lt;/sup&gt;</td>
<td>$-5.9^o &lt; \Delta \alpha &lt; 2.4^o$</td>
<td>$\alpha_{-1} &lt; 0.0037&lt;sup&gt;m&lt;/sup&gt;$</td>
</tr>
<tr>
<td>§ 5</td>
<td>Dark Energy</td>
<td>Constant $w^o$</td>
<td>$-1.37 &lt; 1 + w &lt; 0.32&lt;sup&gt;p&lt;/sup&gt;$</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Evolving $w(z)$&lt;sup&gt;q&lt;/sup&gt;</td>
<td></td>
<td>$-0.11 &lt; 1 + w &lt; 0.14$</td>
</tr>
<tr>
<td>§ 6.1</td>
<td>Neutrino Mass&lt;sup&gt;s&lt;/sup&gt;</td>
<td></td>
<td>$\sum m_\nu &lt; 1.3 \text{ eV}^t$</td>
<td>$\sum m_\nu &lt; 0.61 \text{ eV}^u$</td>
</tr>
<tr>
<td>§ 6.2</td>
<td>Neutrino Species</td>
<td></td>
<td>$N_{eff} &gt; 2.3^v$</td>
<td>$N_{eff} = 4.4 \pm 1.5^w \ (68%)$</td>
</tr>
</tbody>
</table>
• BAO+SN are very powerful in reducing the uncertainty in several ΛCDM parameters.

• Any parameters related to $\Omega_m h^2$ & $H_0$ have improved significantly.
And, we ended up here again...

**TABLE 1**

Summary of the cosmological parameters of ΛCDM model and the corresponding 68% intervals

<table>
<thead>
<tr>
<th>Class</th>
<th>Parameter</th>
<th>WMAP 5-year ML</th>
<th>WMAP+BAO+SN ML</th>
<th>WMAP 5-year Mean</th>
<th>WMAP+BAO+SN Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>$100\Omega_b h^2$</td>
<td>2.268</td>
<td>2.263</td>
<td>2.273 ± 0.062</td>
<td>2.265 ± 0.059</td>
</tr>
<tr>
<td></td>
<td>$\Omega_c h^2$</td>
<td>0.1081</td>
<td>0.1136</td>
<td>0.1099 ± 0.0062</td>
<td>0.1143 ± 0.0034</td>
</tr>
<tr>
<td></td>
<td>$\Omega_b$</td>
<td>0.751</td>
<td>0.724</td>
<td>0.742 ± 0.030</td>
<td>0.721 ± 0.015</td>
</tr>
<tr>
<td></td>
<td>$n_s$</td>
<td>0.961</td>
<td>0.961</td>
<td>0.963$^{+0.014}_{-0.015}$</td>
<td>0.960$^{+0.014}_{-0.013}$</td>
</tr>
<tr>
<td></td>
<td>$\tau$</td>
<td>0.089</td>
<td>0.080</td>
<td>0.087 ± 0.017</td>
<td>0.084 ± 0.016</td>
</tr>
<tr>
<td></td>
<td>$\Delta^2_R (k_0^c)$</td>
<td>$2.41 \times 10^{-9}$</td>
<td>$2.42 \times 10^{-9}$</td>
<td>$(2.41 \pm 0.11) \times 10^{-9}$</td>
<td>$(2.457^{+0.0092}_{-0.0093}) \times 10^{-9}$</td>
</tr>
<tr>
<td>Derived</td>
<td>$\sigma_8$</td>
<td>0.787</td>
<td>0.811</td>
<td>0.796 ± 0.036</td>
<td>0.817 ± 0.026</td>
</tr>
<tr>
<td></td>
<td>$H_0$</td>
<td>72.4 km/s/Mpc</td>
<td>70.3 km/s/Mpc</td>
<td>71.9$^{+2.6}_{-2.7}$ km/s/Mpc</td>
<td>70.1 ± 1.3 km/s/Mpc</td>
</tr>
<tr>
<td></td>
<td>$\Omega_b$</td>
<td>0.0432</td>
<td>0.0458</td>
<td>0.0441 ± 0.0030</td>
<td>0.0462 ± 0.0015</td>
</tr>
<tr>
<td></td>
<td>$\Omega_c$</td>
<td>0.206</td>
<td>0.230</td>
<td>0.214 ± 0.027</td>
<td>0.233 ± 0.013</td>
</tr>
<tr>
<td></td>
<td>$\Omega_m h^2$</td>
<td>0.1308</td>
<td>0.1363</td>
<td>0.1326 ± 0.0063</td>
<td>0.1369 ± 0.0037</td>
</tr>
<tr>
<td></td>
<td>$z_{\text{reion}}$</td>
<td>11.2</td>
<td>10.5</td>
<td>11.0 ± 1.4</td>
<td>10.8 ± 1.4</td>
</tr>
<tr>
<td></td>
<td>$t_0$</td>
<td>13.69 Gyr</td>
<td>13.72 Gyr</td>
<td>13.69 ± 0.13 Gyr</td>
<td>13.73 ± 0.12 Gyr</td>
</tr>
</tbody>
</table>
Summary

• A simple, yet mysterious $\Lambda$CDM still fits the WMAP data, as well as the other astrophysical data sets.

• We did everything we could do to find deviations from $\Lambda$CDM, but failed.

• Significant improvements in limits on the deviations
  • Most notably, $r<0.2$ (95% CL), and $n_s>1$ is now disfavored regardless of $r$.
  • Many popular inflation models have been either ruled out, or being in danger!

• Significant improvements in $\Lambda$CDM parameters.
Looking Ahead...

• With more WMAP observations, exciting discoveries may be waiting for us. Two examples for which we might be seeing some hints from the 5-year data:
  
• Non-Gaussianity: If $f_{NL} \sim 50$, we will see it at the 3 sigma level with 9 years of data.

• Gravitational waves ($r$) and tilt ($n_s$): $m^2\phi^2$ can be pushed out of the favorable parameter region
  
  • $n_s > 1$ would be convincingly ruled out regardless of $r$. 
