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
- WMAP is capable of measuring the temperature contrast down to better than one part in millionth.
**WMAP Spacecraft**

**Radiative Cooling: No Cryogenic System**

- Line of sight
- Back to back Gregorian optics, 1.4 x 1.6 m primaries
- Focal plane assembly feed horns
- Secondary reflectors
- Thermally isolated instrument cylinder
- Upper omni antenna
- Passive thermal radiator
- Medium gain antennae
- Deployed solar array w/ web shielding
- Warm spacecraft with:
  - Instrument electronics
  - Attitude control/propulsion
  - Command/data handling
  - Battery and power control

Radiative Cooling: No Cryogenic System
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.
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
• **Universe today**
  
  • Age: **13.72 +/- 0.12** Gyr
  
  • Atoms: **4.56 +/- 0.15** %
  
  • Dark Matter: **22.8 +/- 1.3**%
  
  • Vacuum Energy: **72.6 +/- 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

T(µK)

-200

+200
The Spectral Analysis

Measurements totally signal dominated to $l=530$

Much improved measurement of the 3rd peak!
The Cosmic Sound Wave

Angular Power Spectrum

$\frac{l(l+1)C_l}{2\pi}$ [$\mu$K$^2$]

Multiplicity moment $l$

Note consistency around the 3rd-peak region

WMAP 5yr  
Acbar  
Boomerang  
CBI
The Cosmic Sound Wave

- We measure the composition of the Universe by analyzing the wave form of the cosmic sound waves.
CMB to $\Omega_{bh}h^2$ & $\Omega_{mh}h^2$

- 1-to-2: baryon-to-photon; 1-to-3: matter-to-radiation ratio
- $\Omega_{\gamma} = 2.47 \times 10^{-5} h^{-2}$ & $\Omega_r = \Omega_{\gamma} + \Omega_{\nu} = 1.69 \Omega_{\gamma} = 4.17 \times 10^{-5} h^{-2}$
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)
Decisive confirmation of basic theoretical understanding of perturbations in the universe!
5-Year E-Mode Polarization Power Spectrum at Low $l$

5-sigma detection of the E-mode polarization at $l=2-6$. (Errors include cosmic variance)

Black Symbols are upper limits
B-modes

- No detection of B-mode polarization yet.
- I will come back to this later.
Polarization From Reionization

- CMB was emitted at $z=1090$.
- Some fraction (~9%) of CMB was re-scattered in a reionized universe: \textit{erased temperature anisotropy, but created polarization}.
- The reionization redshift of $\sim 11$ would correspond to 400 million years after the Big-Bang.

\[ z=1090, \tau \sim 1 \]

\[ z \sim 11, \tau = 0.087 \pm 0.017 \text{ (WMAP 5-year)} \]

\[ z=0 \]
• 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 -> Inflation

\[ I(l+1)C_l T^2/2\pi \]
“Red” Spectrum: $n_s < 1$
"Blue" Spectrum: $n_s > 1$
Expectations From 1970’s: $n_s=1$

- Metric perturbations in $g_{ij}$ (let’s call that “curvature perturbations” $\Phi$) is related to $\delta$ via

- $k^2\Phi(k)=4\pi G \rho a^2 \delta(k)$

- Variance of $\Phi(x)$ in position space is given by

- $\langle \Phi^2(x) \rangle = \int \ln k k^3 |\Phi(k)|^2$

- In order to avoid the situation in which curvature (geometry) diverges on small or large scales, a “scale-invariant spectrum” was proposed: $k^3 |\Phi(k)|^2 = \text{const.}$

- This leads to the expectation: $P(k)=|\delta(k)|^2=k$ ($n_s=1$)

- Harrison 1970; Zel’dovich 1972; Peebles & Yu 1970
Is $n_s$ different from ONE?

- WMAP-alone: $n_s=0.963 \pm 0.014$ (Dunkley et al.)
- 2.5-sigma away from $n_s=1$, “scale invariant spectrum”
- $n_s$ is degenerate with $\Omega_b h^2$; thus, we can’t really improve upon $n_s$ further unless we improve upon $\Omega_b h^2$
Deviation from $n_s = 1$

- This was expected by many inflationary models.

- In $n_s$–$r$ plane (where $r$ is called the “tensor-to-scalar ratio,” which is $P(k)$ of gravitational waves divided by $P(k)$ of density fluctuations) many inflationary models are compatible with the current data.

- Many models have been excluded also.
Searching for Primordial Gravitational Waves in CMB

• Not only do inflation models produce density fluctuations, but also primordial gravitational waves
• Some predict the observable amount ($r > 0.01$), some don’t
  • Current limit: $r < 0.22$ (95%CL)
• Alternative scenarios (e.g., New Ekpyrotic) don’t
• A powerful probe for testing inflation and testing specific models: next “Holy Grail” for CMBist
If all the other parameters ($n_s$ 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)
Lowering a “Limbo Bar”

- $\lambda \phi^4$ is totally out. (unless you invoke, e.g., non-minimal coupling, to suppress $r$...)
- $m^2 \phi^2$ is within 95% CL.
  - Future WMAP data would be able to push it to outside of 95% CL, if $m^2 \phi^2$ is not the right model.
- N-flation $m^2 \phi^2$ (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
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

- Peak Locations → Distance to the LSS
- First Peak Height & Third
- Second Peak Height → Baryon/Photon Density Ratio
- Overall Tilt → Amplitude Ratio of Large/Small Scale
- Temperature-polarization correlation (TE)
  - Radiation-matter Adiabaticity
  - Gravitational waves
- Constraints on Inflation Models

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Gravitational waves
Temperature-polarization correlation (TE)
Radiation-matter Adiabaticity

Constraints on Inflation Models
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 cosmological distance measurements:
  
  • *Luminosity Distances* from Type Ia Supernovae (SN)
  
  • *Angular Diameter Distances* from the Baryon Acoustic Oscillations (BAO) in the distribution of galaxies
Example: Flatness

- 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
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.

- Latest “Union” supernova compilation (Kowalski et al.)
• The same acoustic oscillations should be hidden in this galaxy distribution...
• 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 $w=-1$
(i.e., dark energy being a cosmological constant)

The constraint driven mostly by WMAP+BAO
How Big Is Our Universe?

• By definition, the curvature radius of the universe is given 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 (\( \Omega_k < 0 \)): \( R > 22h^{-1}\text{Gpc} \)

• The particle horizon today is \( 9.7h^{-1}\text{Gpc} \)

• The curvature radius of the universe is at least 3 times as large as the observable universe.
How Long Did Inflation Last?

• The universe had expanded by $e^{N_{\text{tot}}}$ during inflation.

• 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 TeV
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.

- **Detection of non-Gaussianity would be a breakthrough in cosmology**
Getting the Most Out of Fluctuations, $\delta(x)$

- In Fourier space, $\delta(k) = A(k)\exp(i\varphi_k)$

- **Power**: $P(k) = \langle |\delta(k)|^2 \rangle = A^2(k)$

- **Phase**: $\varphi_k$

- We can use the observed distribution of...
  - matter (e.g., galaxies, gas)
  - radiation (e.g., Cosmic Microwave Background)

- to learn about both $P(k)$ and $\varphi_k$. 
What About Phase, $\varphi_k$

- There were expectations also:
  - Random phases! (Peebles, ...)
  - Collection of random, uncorrelated phases leads to the most famous probability distribution of $\delta$:

Gaussian Distribution
Gaussian?
The one-point distribution of WMAP map looks pretty Gaussian.

- Left to right: Q (41GHz), V (61GHz), W (94GHz).

Deviation from Gaussianity is small, if any.
Triangles on the Sky: 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_{NL}(local) < 111 (95% CL)
• -151 < f_{NL}(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.
Grading Inflation

- **Flatness**: $-0.0179 < \Omega_k < 0.0081$ (not assuming $w=-1$!)
- **Non-adiabaticity**: <8.9% (axion DM); <2.1% (curvaton DM)
- **Non-Gaussianity**: -9 < Local < 111; -151 < Equilateral < 253
- **Tilt** (for $r=0$): $n_s=0.960 \pm 0.013$ [68% CL]
- **Gravitational waves**: $r < 0.22$
Effective Number of Neutrino Species, $N_{\text{eff}}$

- For relativistic neutrinos, the energy density is given by
  \[
  \rho_{\nu} = N_{\text{eff}} \left(\frac{7\pi^2}{120}\right) T_{\nu}^4
  \]
  where $N_{\text{eff}}=3.04$ for the standard model, and
  \[
  T_{\nu} = \left(\frac{4}{11}\right)^{1/3} T_{\text{photon}}
  \]

- Adding more relativistic neutrino species (or any other relativistic components) delays the epoch of the matter-radiation equality, as
  \[
  1+z_{\text{EQ}} = \left(\Omega_{m}h^2/2.47\times10^{-5}\right) / (1+0.227N_{\text{eff}})
  \]
• It is $z_{\text{EQ}}$ that is observable from CMB.

• If we fix $N_{\text{eff}}$, we can determine $\Omega_m h^2$; otherwise...
$N_{\text{eff}} - \Omega_m h^2$ Degeneracy

- $N_{\text{eff}}$ and $\Omega_m h^2$ are totally degenerate!

- Adding information on $\Omega_m h^2$ from the distance measurements (BAO, SN, HST) breaks the degeneracy:
  - $N_{\text{eff}} = 4.4 \pm 1.5 \,(68\%\text{CL})$
• $N_{\text{eff}}$ and $\Omega_m h^2$ are totally degenerate - but, look.

• **WMAP-only lower limit is not $N_{\text{eff}}=0$**

• $N_{\text{eff}}>2.3$ (95%CL) [Dunkley et al.]
Cosmic/Laboratory Consistency

- From WMAP \((z=1090)\)+BAO+SN
  - \(N_{\text{eff}} = 4.4 \pm 1.5\)

- From the Big Bang Nucleosynthesis \((z=10^9)\)
  - \(N_{\text{eff}} = 2.5 \pm 0.4\) (Gary Steigman)

- From the decay width of Z bosons measured in lab
  - \(N_{\text{neutrino}} = 2.984 \pm 0.008\) (LEP)
The local distance measurements (BAO) help determine the neutrino mass by giving $H_0$.

- \( \text{Sum}(m_{\nu}) < 0.67 \text{ eV} \) (95% CL) -- independent of the normalization of the large scale structure.
Summary

- Errorbars on the simplest, 6-parameter ΛCDM model are tightly constrained by WMAP-data only, and even more tightly (especially matter density and amplitude of fluctuations) by combining low-z distance measurements.
• We did everything we could do to find deviations from $\Lambda$CDM, but failed.

• Well, we still don’t know what DE or DM is.
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 ($n_s$): $m^2 \varphi^2$ can be pushed out of the favorable parameter region

    • More, maybe seeing a hint of it if $m^2 \varphi^2$ is indeed the correct model?!