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

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Texas Cosmology Center (TCC)  
The University of Texas Austin

• The new Cosmology Center, founded in January 2009, at the University of Texas at Austin!

• www.tcc.utexas.edu

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Physics
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Steven Weinberg
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
- upper omni antenna
- medium gain antennae
- deployed solar array w/ web shielding
- thermally isolated instrument cylinder
- secondary reflectors
- focal plane assembly feed horns
- passive thermal radiator

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

60K

90K

300K
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.
Hinshaw et al.
Galaxy-cleaned Map

Hinshaw et al.

WMAP 5-year
WMAP 5-Year Papers


• **Hill et al.**, “Beam Maps and Window Functions” *ApJS, 180, 246*

• **Gold et al.**, “Galactic Foreground Emission” *ApJS, 180, 265*

• **Wright et al.**, “Source Catalogue” *ApJS, 180, 283*

• **Nolta et al.**, “Angular Power Spectra” *ApJS, 180, 296*

• **Dunkley et al.**, “Likelihoods and Parameters from the WMAP data” *ApJS, 180, 306*

• **Komatsu et al.**, “Cosmological Interpretation” *ApJS, 180, 330*
WMAP 5-Year Science Team

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Special Thanks to WMAP Graduates!

- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- L. Verde
Universe today

- Age: $13.72 \pm 0.12$ Gyr
- Atoms: $4.56 \pm 0.15\%$
- Dark Matter: $22.8 \pm 1.3\%$
- Vacuum Energy: $72.6 \pm 1.5\%$

When CMB was released 13.7 B yrs ago

- A significant contribution from the cosmic neutrino background
How Did We Use This Map?
Measurements totally signal dominated to $l=530$

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

Note consistency around the 3rd-peak region
The Cosmic Sound Wave

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

- 1-to-2: baryon-to-photon; 1-to-3: matter-to-radiation ratio
- $\Omega_\gamma = 2.47 \times 10^{-5} h^{-2}$ & $\Omega_r = \Omega_\gamma + \Omega_\nu = 1.69 \Omega_\gamma = 4.17 \times 10^{-5} h^{-2}$
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 $T_\nu = (4/11)^{1/3} T_{\text{photon}}$

- Adding more relativistic neutrino species (or any other relativistic components) delays the epoch of the matter-radiation equality, as
  \[ 1 + z_{\text{EQ}} = \left( \frac{\Omega_m h^2}{2.47 \times 10^{-5}} \right) / (1 + 0.227 N_{\text{eff}}) \]
3rd-peak to $z_{EQ}$

- It is $z_{EQ}$ that is observable from CMB.
- If we fix $N_{eff}$, we can determine $\Omega_m h^2$; otherwise...
• $N_{\text{eff}}$ and $\Omega_m h^2$ are 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%CL)
WMAP-only Lower Limit

- $N_{\text{eff}}$ and $\Omega_m h^2$ are degenerate - but, look.
- **WMAP-only lower limit is not $N_{\text{eff}}=0$**
- $N_{\text{eff}}>2.3$ (95%CL) [Dunkley et al.]
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.
• Multiplicative phase shift is due to the change in $z_{\text{equality}}$
  • Degenerate with $\Omega_m h^2$
• Additive phase shift is due to neutrino perturbations
  • No degeneracy
  (Bashinsky & Seljak 2004)

$\Delta \chi^2 = 8.2 \rightarrow 99.5\% \text{ CL}$
Cosmic/Laboratory Consistency

- From WMAP\((z=10^{9.0})+BAO+SN\)
  - \(N_{\text{eff}} = 4.4 \pm 1.5\)
- 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)
$\Sigma m_\nu$ from CMB alone

- There is a simple limit by which one can constrain $\Sigma m_\nu$ using the primary CMB from $z=1090$ alone (ignoring gravitational lensing of CMB by the intervening mass distribution).

- When all of neutrinos were lighter than $\sim 0.6$ eV, they were still relativistic at the time of photon decoupling at $z=1090$ (photon temperature $3000K=0.26eV$).

  - $<E_\nu> = 3.15(4/11)^{1/3}T_{photon} = 0.58$ eV

- Neutrino masses didn’t matter if they were relativistic!

- For degenerate neutrinos, $\Sigma m_\nu = 3.04 \times 0.58 = 1.8$ eV

  - If $\Sigma m_\nu \ll 1.8$eV, CMB alone cannot see it
CMB + $H_0$ Helps

- WMAP 5-year alone: $\sum m_\nu < 1.3\text{eV}$ (95%CL)
- WMAP+BAO+SN: $\sum m_\nu < 0.67\text{eV}$ (95%CL)
- Where did the improvement comes from? It’s the present-day Hubble expansion rate, $H_0$
Neutrino Subtlety

• For $\Sigma m_\nu << 1.8$eV, neutrinos were relativistic at $z=1090$

• But, we know that $\Sigma m_\nu > 0.05$eV from neutrino oscillation experiments

• This means that neutrinos are definitely non-relativistic today!

• So, today's value of $\Omega_m$ is the sum of baryons, CDM, and neutrinos: $\Omega_m h^2 = (\Omega_b + \Omega_c)h^2 + 0.0106(\Sigma m_\nu/1$eV)
Matter-Radiation Equality

• However, since neutrinos were relativistic before $z=1090$, the matter-radiation equality is determined by:

  $1+z_{\text{EQ}} = (\Omega_b+\Omega_c)h^2 / 4.17 \times 10^{-5}$ (observable by CMB)

• Now, recall $\Omega_m h^2 = (\Omega_b+\Omega_c)h^2 + 0.0106(\sum m_\nu/1\text{eV})$

• For a given $\Omega_m h^2$ constrained by BAO+SN, adding $\sum m_\nu$ makes $(\Omega_b+\Omega_c)h^2$ smaller $\rightarrow$ smaller $z_{\text{EQ}}$ $\rightarrow$ Radiation Era lasts longer

• This effect shifts the first peak to a lower multipole
\[ \Sigma m_\nu: \text{Shifting the Peak To Low-}l \]

- But, lowering \( H_0 \) shifts the peak in the opposite direction. So...
Shift of Peak Absorbed by $H_0$

- Here is a catch:
  - Shift of the first peak to a lower multipole can be canceled by lowering $H_0$!

- Same thing happens to curvature of the universe: making the universe positively curved shifts the first peak to a lower multipole, but this effect can be canceled by lowering $H_0$.

- So, 30% positively curved universe is consistent with the WMAP data, IF $H_0=30\text{km/s/Mpc}$

*Ichikawa, Fukugita & Kawasaki (2005)*
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)

Symbols are upper limits
Polarization From Reionization

- CMB was emitted at $z=1090$.
- Some fraction ($\sim 9\%$) of CMB was re-scattered in a reionized universe: *erased temperature anisotropy, but created polarization*.
- The reionization redshift of $\sim 11$ would correspond to 400 million years after the Big-Bang.
\( z_{\text{reion}} = 6 \) is Excluded

- 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 \( z \sim 6 \). (The 3-sigma lower bound is \( z_{\text{reion}} > 6.7 \).)
B-modes

- No detection of B-mode polarization yet.
- I will come back to this later.
Tilting = Primordial Shape $\rightarrow$ Inflation
“Red” Spectrum: $n_s < 1$
“Blue” Spectrum: $n_s > 1$
Getting rid of the Sound Waves

Angular Power Spectrum

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

Large Scale

Small Scale

Primordial Ripples

Multipole moment \( \ell \)
The Early Universe Could Have Done This Instead

Angular Power Spectrum

More Power on Large Scales

$\ell(l+1)C_\ell^{TT}/2\pi [\mu K^2]$
More Power on Small Scales
\((n_s > 1)\)
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: $P(k) = |\delta(k)|^2 = k^{n_s}$ ($n_s = 1$)

- Harrison 1970; Zel’dovich 1972; Peebles & Yu 1970
• WMAP-alone: $n_s = \mathbf{0.963} \pm 0.014 \pm 0.015$ (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
How GW Affects CMB

• 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

Komatsu et al. 48
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
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.
Inflation Likes This Result

- According to inflation (Guth & Yi; Hawking; Starobinsky; Bardeen, Steinhardt & Turner), CMB anisotropy was created from **quantum fluctuations of a scalar field in Bunch-Davies vacuum** during inflation.

- Successful inflation (with the expansion factor more than $e^{60}$) *demands* the scalar field be almost interaction-free.

- The wave function of free fields in the ground state is a Gaussian!
But, Not Exactly Gaussian

• Of course, there are always corrections to the simplest statement like this

• For one, inflaton field does have interactions. They are simply weak – of order the so-called slow-roll parameters, $\varepsilon$ and $\eta$, which are $O(0.01)$
Simplified Treatment

• Let’s try to capture field interactions, or whatever non-linearities that might have been there during inflation, by the following simple, order-of-magnitude form (Komatsu & Spergel 2001):

  \[ \Phi(x) = \Phi_{\text{gaussian}}(x) + f_{\text{NL}} [\Phi_{\text{gaussian}}(x)]^2 \]

• One finds \( f_{\text{NL}} = O(0.01) \) from inflation (Maldacena 2003; Acquaviva et al. 2003)

• This is a powerful prediction of inflation
Why Study Non-Gaussianity?

- Because a detection of $f_{NL}$ has a best chance of **ruling out the largest class of inflation models**.

- Namely, it will rule out inflation models based upon
  - a single scalar field with
  - the canonical kinetic term that
  - rolled down a smooth scalar potential slowly, and
  - was initially in the Bunch-Davies vacuum.

Detection of non-Gaussianity would be a major breakthrough in cosmology.
Tool: Bispectrum

- **Bispectrum = Fourier Trans. of 3-pt Function**
- **The bispectrum vanishes** for Gaussian fluctuations with random phases.
- Any non-zero detection of the bispectrum indicates the presence of (some kind of) non-Gaussianity.
- A sensitive tool for finding non-Gaussianity.
No Detection at >95%CL

- $-9 < f_{NL} < 111$ (95% CL)
- $f_{NL} = 51 \pm 30$ (68% CL)
- Latest reanalysis: $f_{NL} = 38 \pm 20$ (68% CL) [Smith et al.]
- 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.
The WMAP 5-year data indicate that the simplest cosmological model that fits the data has 6 parameters: the amplitude of fluctuations, baryon density, dark matter density, dark energy density, the optical depth, and $n_s$.

Other parameters are consistent with the standard values: $N_\nu=4.4\pm1.5$, $\Sigma m_\nu<0.67\text{eV}$, ...

No detection of gravitational waves ($r<0.22$) or non-Gaussianity ($f_{NL}=38\pm20$) yet

I didn’t have time to talk about it, but the spatial geometry of the universe is flat to 1%, and the dark energy is consistent with C.C. to 10%.
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 $f_{\text{NL}} \sim 40$, we will see it at $\sim 2.5$ 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

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