Wilkinson Microwave Anisotropy Probe
(and Future Directions)

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Dave Wilkinson

(COBE announcement, 4/92)
WMAP
A partnership between NASA/GSFC and Princeton

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WMAP
Movie

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- Licia Verde

Princeton
- Chris Barnes (Microsoft)
- Rachel Bean
- Olivier Dore
- Norm Jarosik
- Lyman Page
- David Spergel
K - 22GHz
Ka - 33GHz
Q - 41GHz
W - 94GHz
Temperature
85% of sky

Best fit model

Temperature-polarization

Prediction based on TT, no free params.

cosmic variance

z<20

z=1089

Multipole moment (l)
Fundamental Findings

A simple flat model with six parameters fits 1,000,000 data points remarkably well.

\[ A, \Omega_b h^2, \Omega_m h^2, h, n_s, \tau \]

We see there must be superhorizon fluctuations from the TE data.

The Einstein-de Sitter model is disfavored by the WMAP CMB data at > 5 sigma.

A closed model fits the data but requires \( H_0 = 33 \) km/sec, in conflict with other non-CMB data. WMAP/NVSS ISW disfavors this as well.
Next steps in constraining models of the $10^{-35}$ s universe.

- Measure $n_s$ and the running of the index.

- Measure or constrain $r$, the tensor to scalar index.
SDSS Movie

File too large

Mark Subbarao & SDSS Collaboration
The spectrum of scalar fluctuations.

Verde et al. 2003

2dFGRS

Lyman alpha

WMAP

z=1089

2D

z<3

3D

and now SDSS as well.

Vera et al. 2003
The scalar index, $n_s$, with six parameters.

\[
\begin{align*}
    n_s &= 0.99 \pm 0.04 & \text{WMAP} \\
    n_s &= 0.98 \pm 0.03 & +\text{SDSS Tegmark et al. 2004} \\
    n_s &= 0.97 \pm 0.02 & +\text{SDSS Galaxies and Lya Seljak et al. 2004}
\end{align*}
\]

Simple models of inflation predict:

\[
    n_s = 0.96 \pm 0.02
\]

This is significant in that it is a clear departure from scale invariance.

We expect $n_s$ to 1% by 2008 from the CMB.
Running of the scalar index.

In the two recent analyses of WMAP plus SDSS there is no evidence for running.

An analysis of CBI+WMAP+LSS shows evidence of running at the 3-sigma level (-0.085+/-0.031) but the CBI team does not place a lot of weight on the result.
Science:
★ Growth of structure
★ Equation of state
★ Neutrino mass
★ Ionization history
★ Inflation
★ Power spectrum

Observations:
★ CMB: \( l > 1000 \)
★ Cluster (SZ, KSZ X-rays, & optical)
★ Diffuse SZ
★ OV
★ Lensing

ACT

X-ray

Optical

Theory

NSF Funded
ACT Collaboration
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UMass
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Arrays of bolometers

Moseley et al, NASA

Bock, JPL/Caltech

Lee, Berkeley

SHARC II 12x32 Popup Array
PI D. Dowell

Torsional yoke attachment

One element of array
Simulations of mm-wave data.

1.4°< 1%
Survey area
≈ 2%
High quality area

150 GHz

SZ Simulation
MBAC on ACT
PLANCK

Statistical uncertainties

SPT and APEX too.

Burwell/Seljak

de Oliveira-Costa
CMB Polarization

- Polarization of the CMB is produced by Thompson scattering of a quadrupolar radiation pattern.

- A component of the polarization is correlated with the temperature anisotropy.

- Whenever there are free electrons, the CMB is polarized.
Ionization History of Universe

Polarization generated at decoupling surface.

Polarization generated by first stars turning on.
Types of Cosmological Perturbations

Scalars: \( \frac{\delta \rho}{\rho}, \mathcal{P}(k) \propto k^{n_s} \)

- Temperature
- E polarization

Tensors \( h \) (GW strain)

- Temperature
- E polarization
- B polarization

\[ r = \frac{\text{Var(Tensors)}}{\text{Var(Scalars)}} \approx 0.27 \] (Maximum)

Khoury et al.
Gravity Waves

Over expanse of universe, one side is displaced 1000 ly with respect to the other.

From L. Boyle & P. Steinhardt
Polarization Spectrum

Current limit on tensors

B modes from tensors only.

\[ \delta T_l^B \propto r^{1/2} \propto E_{\text{infl}}^2 \]

Reionization peak \((z_r=20)\)

Horizon size at decoupling \((z_{\text{dec}}=1089)\)

Test inflation & tau Test T predictions

G-waves decay once inside the horizon.

B modes from lensing of E modes.
On the Verge of Detecting $r$?

$r \leq 0.84 \ (95\% \ cl, \ WMAP)$
$r \leq 0.53 \ (95\% \ cl, \ WMAP + 2dF)$
$r \leq 0.47 \ (95\% \ cl, \ WMAP + SDSS)$
$r \leq 0.36 \ (95\% \ cl, \ WMAP + SDSS + Ly\alpha)$

◆ All come from the temperature anisotropy and will improve. Simple models of inflation are being leaned on!
◆ A possible 95\% cl limit on $r$ from TT is roughly 0.1.
◆ The window for using B modes to detect $r$ will open soon.
The tensor to scalar ratio is being constrained by the low $l$ region of the TT spectrum.

When $r$ is added to the mix of parameters (making 7), $n_s$ rises to compensate. There is a $n_s$-$r$ degeneracy*.

\[
\begin{align*}
\text{r}<0.84 & \quad n_s = 1.064^{+0.66}_{-0.059} \quad \text{WMAP} \\
\text{r}<0.47 & \quad n_s = 1.012^{+0.049}_{-0.036} \quad \text{WMAP+SDSS Tegmark et al} \\
\text{r}<0.38 & \quad n_s = 1.00 \pm 0.03 \quad \text{WMAP+SDSS+Lyα Seljak et al}
\end{align*}
\]

This is starting to lean on $r=0.27$ for simple models of inflation.

*and tau, A too.
Sensitivity Advances

COBE

WMAP

Planck

Inflation Probe

ΔT = 18 μK

>x60

>x20

>x50?