Announcements:

- PS6 out, due in class *Wednesday* next week
  - Updated version posted April 22!
  Mistakes were made. Q2b, Q3b now corrected/clarified.
  Management regrets the error.
- **ICES** available online staring *today* – please do it!
  written comments most helpful to future generations

Last time: CMB anisotropies

*Q: what quantity is plotted to show CMB “wiggles”?*

*Q: what is the physical origin of CMB “wiggles”?*
CMB Anisotropies and Cosmological Parameters

Small angular scales: peaks at density extrema can measure peak scales ($\ell$ positions), amplitudes

Peak Positions
recall: all oscillations begin together (in phase) then scale $k$ has phase $\omega \eta = c_s k \eta$
observe: density at recomb, when phase is $c_s k d_{\text{rec}}$
peaks at extrema
1st peak: scale at 1st compression, 2nd peak: 1st rarefaction ...

$$\lambda = 2c_s d_{\text{rec,com}} \left(1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \cdots \right)$$ (1)

$\sim$ harmonics, first peak scale $\sim 2d_{s,\text{hor}} \sim d_{\text{hor,com}}$
angular diameter measurement! standard ruler = comoving horizon
sensitive to geometry → curvature
⇒ peak positions: $\Omega_0$

why? in flat matter-dominated U: physical particle horizon is
$$d_{\text{hor,phys}}(z) = (1+z)d_{\text{hor,com}}(z) = (1_z) \int_0^zd\tau/a2\Omega_m^{-1/2}d_{\text{H,0}}(1+z)^{1/2}$$

angular diameter distance is
$$d_A(z) = \frac{r(z)}{1+z} = 2\Omega_m^{-1/2}d_{\text{H,0}}(1+z)$$

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and so expect sound horizon angular diameter
$$\vartheta_{\text{hor,s}} = \frac{c_s}{c}\vartheta_{\text{hor}} = \frac{c_s}{c} \frac{d_{\text{hor,phys}}(z_{\text{rec}})}{d_A(z_{\text{rec}})} \approx \frac{1}{\sqrt{3}} \frac{1}{\sqrt{1+z_{\text{rec}}}} \sim 1^\circ$$

$\Omega_0 = 1$

Q: what about amplitudes? 1st peak? 2nd peak?
Acoustic Peak Amplitudes

Amplitude measures degree of compression/rarefaction
→ strength of driving force → matter density
mostly DM density, but baryons too

Effect of baryons: alter the gravitational potential well
▷ during compression: baryons make well deeper
▷ during rarefaction: baryons make well shallower
Net effect: higher $\Omega_{\text{baryon}}$ → bigger odd peaks (compression)
smaller even (rarefaction) peaks

If measure one of each, e.g., 1st + 2nd peaks → get $\Omega_B$!
★ CMB is cosmic baryometer!
★ independent of BBN (also more precise)
As we saw: decent CMB-BBN concordance
...but Li problem remains
CMB Polarization

Recall: pre-recombination, photons coupled to baryons via Thompson scattering with electrons
Key fact: Thompson scattering is anisotropic and polarized
intensity and polarization of scattered radiation scales as

\[
\frac{d\sigma_T}{d\Omega} \propto |\hat{\epsilon}_{\text{in}} \cdot \hat{\epsilon}_{\text{sc}}|^2 = \cos^2 \theta
\]  

(5)

max scattered intensity & pol’n in plane normal to initial pol’n
zero scattered intensity in direction of initial pol’n

classical picture: \( e^- \) as dipole antenna
incident polarized wave accelerates \( e^- \)
\[ \rightarrow \text{azimuthally symmetric radiation, peaks in } \theta = 0 \text{ plane} \]

note: since \( \cos^2 \theta \propto \cos 2\theta \), scattered rad has 180\(^0\) periodicity
\[ \rightarrow \text{a “pole” every } 90^0: \text{quadrupole} \]
Polarization and Inhomogeneity

Pre-recomb: repeated Thompson scattering
randomizes polarization $\rightarrow$ CMB unpolarized

But at recomb, last scattering evens “uncompensated”
• if plasma homogeneous: still no net polarization
• but inhomogeneities $\rightarrow$ net linear polarization in CMB

How? consider point at 90° corner of hot region
• Q: is there polarization? if so, orientation?

Now consider “checkerboard vertex” (local quadrupole in $T$)
$\rightarrow$ net linear polarization towards us, aligned w/ “cold” axis
www: cool Wayne Hu movie
Now consider point at hot/cold “wall”
locally sees dipole $T$ anisotropy
net polarization towards us: zero! $Q$: why?

$Q$: what about edge of circular hot spot? cold spot?
polarization tangential (ring) around hot spots
radial (spokes) around cold spots
(superpose to “+” = zero net polarization—check!)

www: WMAP polarization observations of hot and cold spots

Note: polarization & T anisotropies \textit{linked}
→ consistency test for CMB theory and hence hot big bang
Polarization Observed

First detection: pre-WMAP!
★ DASI (2002) ground-based interferometer
at level predicted based on $T$ anisotropies! Woo hoo!

WMAP (2003): first polarization-$T$ correlation function

WMAP (2006):
● better statistics
● also polarization autocorrelation
★ used $T$-pol’n links to get model-independent
  3-D density power spectrum: consistent with scale invariant!
CMB Summary and Outlook

What has the CMB done for us
- confirmed hot, dense, smooth early universe
- measured primordial power spectrum, consistent w/ inflation
- seen acoustic peaks
- measured a wealth of cosmological parameters
- seen polarization: confirms underlying physics model

What will the CMB do for us
- better polarization $\rightarrow$ gravity wave signal from inflation!
- CMB as background illumination for structure formation
  - SZ effect, 21-cm, ...
- stay tuned!