Astro 507
Lecture 38
April 28, 2014

Announcements:

- **Problem Set 6 extended until Friday May 1**
  so office hours Thursday are available
- **ICES** available online – please do it!

Last time: began CMB anisotropies
Q: physical origin of CMB ΔT on scales $\gg d_{\rm hor,recomb}$?
on scales $\ll d_{\rm hor,recomb}$?
Q: largest scale experiencing oscillations?

Today: observing anisotropies and mining cosmological gold
Q: how to measure CMB temperature anisotropies? challenges?
techniques?

CMB Anisotropy Observations: Strategy

- achieve high sensitivity, remove systematics
  make a "difference experiment"
  i.e., measure δT directly, don't subtract
- observe as much of the sky as possible (or as needed!)
  balloons/ground: limited coverage
  satellites (COBE, WMAP, Planck): all-sky
- remove Galactic contamination: "mask" plane
- recover Θ for observed region

- decompose into spherical harmonics $Y_{\ell m}$
- construct power spectrum $\ell(\ell+1)C_\ell$
- report results
- collect thousands of citations, prominent Prizes

CMB Temperature Anisotropies: Results

COBE (1993)

- first detection of $\delta T/T \neq 0$
- receiver horn angular opening $\sim 8^\circ$
  $\rightarrow$ only sensitive to large angular scales
  i.e., superhorizon size
- found $(\delta T/T)_{\rm rms} \sim 10^{-5}$
- power $\ell(\ell+1)C_\ell$ flat $\rightarrow$ implies $P(k) \sim k$!
  $n = 1$ spectrum: scale invariant!

Interregnum (late 90's, early 00's)

- ground-based, balloons confirmed anisotropy
- acoustic peaks discovered
  strong indication of first peak

WMAP (2003–2010)

- first all-sky survey of small angular scales
- $n = 1$ confirmed, indication of small tilt $n - 1 \neq 0$?
  consistent with inflation! and non-trivially so!
- acoustic peaks mapped: good measurement of 1st, 2nd
  detection of third
- first peak: $\ell \sim 200$ horizon at recomb!
- power dropoff seen at large ℓ
  $\rightarrow$ nonzero thickness of last scattering
  due to photon diffusion, non-instantaneous decoupling

Planck (2013–present)

- exquisite measurements of cosmological parameters
- small deviation from scale invariance measured at high confidence
- no detection of non-Gaussianity
- sensitivity to N_{eff} and Y_{p}

2014: polarization results to come!

CMB Anisotropies and Cosmological Parameters

Small angular scales: peaks at density extrema
can measure peak scales (ℓ 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 $c_s k d_{\text{rec}}$

Q: what is largest scale to show δT extremum? what extremum?
Q: what is next largest scale to show extremum?
Q: implications?

oscillations begin together (in phase)
at recomb, scale k has phase $c_s k d_{\rm rec}$

peaks at extrema
1st peak: scale that just reached 1st compression
2nd peak: scale that just reach 1st rarefaction
3rd peak: scale that just reach 2nd compression...

peak locations: comoving wavelengths

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

harmonics, first peak scale $\sim 2 d_{\rm s,hor} \sim d_{\rm hor,com}$

Q: what do we actually measure on CMB sky? implications?

fluctuation size on sky = angular diameter measurement!

standard ruler=comoving horizon

sensitive to geometry → curvature

⇒ peak positions: Ω_0

why? in flat matter-dominated U: physical particle horizon is

$d_{\rm hor,phys}(z) = (1+z) d_{\rm hor,com}(z) = (1_z) \int_0 dt/a 2\Omega_{\rm m}^{-1/2} d_{\rm H,0}(1+z)^{1/2}$

angular diameter distance is

$$d_{\rm A}(z) = \frac{r(z)}{1+z} = 2\Omega_{\rm m}^{-1/2} d_{\rm H,0}(1+z) \qquad (2)$$

and so expect *sound horizon* angular diameter

$$\vartheta_{\rm hor,s} = \frac{c_s}{c}\vartheta_{\rm hor} = \frac{c_s}{c}\frac{d_{\rm hor,phys}(z_{\rm rec})}{d_{\rm A}(z_{\rm rec})} \simeq \frac{1}{\sqrt{3}}\frac{1}{\sqrt{1+z_{\rm rec}}} \sim 1^\circ \qquad (3)$$

∞ WMAP: first peak at $\ell_{\rm peak} \sim 200 \to \vartheta_{\rm peak,obs} \sim 1^\circ \to$ $\Omega_0 = 1$

Q: what about amplitudes? 1st peak? 2nd peak?

Acoustic Peak Amplitudes

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

Q: effect of baryons on 1st peak? 2nd peak? other peaks?

Effect of baryons: alter the gravitational potential well

▷ during compression: baryons make well deeper

▷ during rarefaction: baryons make well shallower

Net effect: higher $\Omega_{\text{baryon}} \rightarrow$ bigger odd peaks (compression)

smaller even (rarefaction) peaks

If measure one of each, e.g., 1st + 2nd peaks $\rightarrow$ get Ω_B!

⋆ CMB is cosmic baryometer!

⋆ independent of BBN (also more precise)

As we saw: decent CMB-BBN concordance

...but Li problem remains

Q: why do fluctuations die off at small angular scales?

CMB Damping Tail

so far: assumed recombination *instantaneous*
- decoupling as sharp transition
- all photons have last scattering at same instant

in reality:
last scattering is smooth transition
photon mean free path quickly but smoothly increases
$\rightarrow$ not all photons last scatter at same time
$\rightarrow$ *last scattering surface has nonzero thickness*

expect CMB signal *damping* on scales $\ll$ thickness
$\rightarrow$ on smaller scales, photon scattering diffusive
$\rightarrow$ exponentially suppresses temperature signal

CMB Polarization

Recall: pre-recombination, photons coupled to baryons via Thompson scattering with electrons

Key fact: Thompson scattering is anisotropic and polarized polarization of scattered radiation scales as

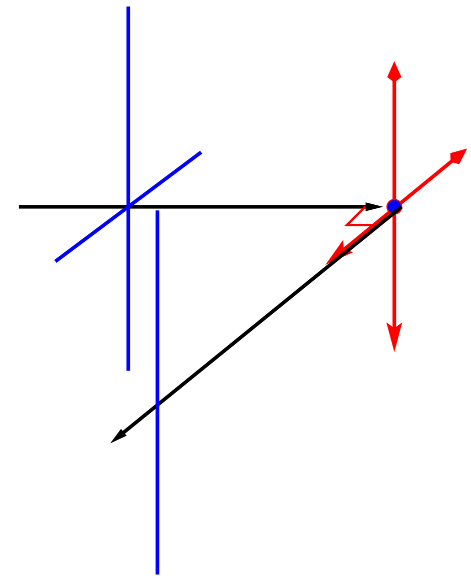
$$\frac{d\sigma_T}{d\Omega} \propto |\hat{\epsilon}_{\rm in} \cdot \hat{\epsilon}_{\rm sc}|^2 = \cos^2\theta \quad (4)$$

where:
$\hat{\epsilon}_{\rm in}$ is *incident photon polarization*
$\hat{\epsilon}_{\rm sc}$ is *scattered photon polarization*
and propagation is transverse: $\hat{\epsilon}_{\rm in} \cdot \hat{n}_{\rm in} = 0$

Q: in what direction is polarization max? min?
Q: why physically? hint: think of e as antenna

max scattered polarization when in plane normal to initial pol'n
zero scattered intensity in direction of initial pol'n

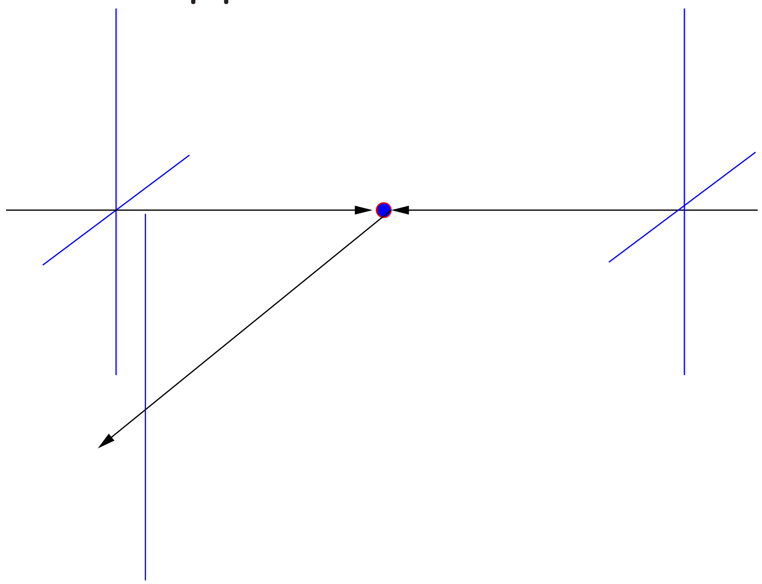
classical picture: e^- as dipole antenna
incident polarized wave accelerates e^-
  $\rightarrow$ azimuthally symmetric radiation,
  peaks in $\theta = 0$ plane



note: since $\cos^2\theta \propto \cos 2\theta$, scattered rad has 180^0 periodicity
$\rightarrow$ a "pole" every 90^0: quadrupole

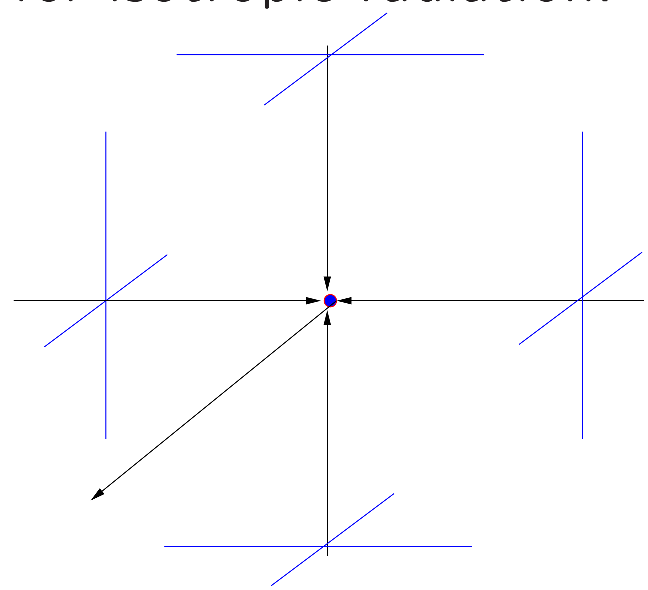
Q: what if unpolarized radiation from 2 opposite directions?
Q: what if isotropic unpolarized radiation?

from opposite incident directions:



still linearly polarized!

for isotropic radiation:



unpolarized!

...as demanded by symmetry

Polarization and Inhomogeneity

Pre-recomb: repeated Thompson scattering
randomizes polarization → CMB unpolarized

But at recomb, last scattering evens "uncompensated"

- if plasma homogeneous: still no net polarization
- but inhomogeneities → net linear polarization in CMB

Consider point on hot-cold "wall"

Q: what is scattered polarization? why?

Q: what temperature pattern seen at point?