The Physics of CMB Anisotropies

and their

Cosmological Implications

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CMB Isotropy

Actual Temperature Data
Dipole Anisotropy

our motion
1 part in 1000

COBE 1992
Large–Angle Anisotropies

10°–90° anisotropy
1 part in 100000

COBE 1992
Ringing in the New Cosmology

ΔT (µK)

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10 100 1000
Acoustic Oscillations
A Brief Thermal History

- CMB photons hotter at high redshift $z$
- At $z \sim 1000$, $T \sim 3000$K: photons ionize hydrogen

Microwaves

Cosmological Redshift

Recombination
$z \sim 1000; T \sim 3000$K

Photon-Baryon Plasma
A Brief Thermal History

- At $z > 1000$, photon-baryon plasma: perfect fluid
- Photons provide pressure; baryons add inertia
Gravitational Ringing

- Potential wells = inflationary seeds of structure
- Fluid falls into wells, pressure resists: acoustic oscillations
Plane Waves

- Potential wells: part of a fluctuation spectrum
- Plane wave decomposition
Harmonic Modes

- Frequency proportional to wavenumber: $\omega = kc_s$
- Twice the wavenumber = twice the frequency of oscillation
Extrema = Peaks

• **First peak** = mode that just compresses

• **Second peak** = mode that compresses then rarefies: *twice* the wavenumber

• **Harmonic peaks**: 1:2:3 in wavenumber

\[ k_1 = \frac{\pi}{\text{sound horizon}} \]

\[ k_2 = 2k_1 \]

\[ \Delta T/T \]

\[ -|\Psi|/3 \]
Seeing Sound

- Oscillations frozen at recombination
- Compression=hot spots, Rarefaction=cold spots
- Extrema are harmonics of distance sound travels
Peaks in Angular Power

- Oscillations frozen at recombination
- Distant hot and cold spots appear as temperature anisotropies
The First Peak
First Peak Precisely Measured

\[ l_1 \approx 200 \]

\[ \Delta l \approx 250 \]
Spatial Curvature

- Physical scale of peak = distance sound travels
- Angular scale measured: comoving angular diameter distance test for curvature
Curvature in the Power Spectrum

- Features scale with angular diameter distance
- Angular location of the first peak
A (Nearly?!) Flat Universe

- Hubble constant! Baryons: calibrate rulers

- Slightly closed or young universe marginally preferred

- BOOMERanG
- MAXIMA
- closed open
- $\Omega_m < 0.8$
- $h < 0.025$

- $\Lambda$ vs $\Omega_m$
What Makes It Flat?

- Info on $H_0$, $\Omega_m$, or $\Omega_\Lambda$ breaks degeneracy
  
  $H_0$: currently by assuming flatness, future by measuring $\Omega_m h^2$
Concordance!? 

- Consistent and requires missing “dark” energy
The Second Peak
What is it Good For

- **Acoustic nature:** beyond reasonable doubt

- **Inflation:** superhorizon potential perturbations
defects already strongly disfavored: narrow first peak

![Graph showing Power vs l with two curves labeled Inflation 1:2:3 and Isocurvature.](image-url)
What is it Good For

- **Current**: second peak unresolved
- **Amplitude**: constrained to be low
Baryon & Inertia

- **Baryons add inertia** to the fluid
- Equivalent to adding **mass** on a **spring**
- **Same initial conditions**
- **Same null in fluctuations**
- **Unequal amplitudes of extrema**
A Baryon-meter

- Baryons drag the fluid into potential wells
- Enhance compressional peaks (odd) over rarefaction peaks (even)

E.g. suppression of second peak
A Baryon-meter

- Baryons drag the fluid into potential wells
- Enhance *compressional peaks* (odd) over *rarefaction peaks* (even)

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A Baryon-meter

- Baryons drag the fluid into potential wells
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e.g. suppression of second peak
Baryons in the Power Spectrum

ΔT (μK)

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l
Second Peak

- Second peak is (too?) suppressed
- At least as many baryons as nucleosynthesis
  (50% more preferred
  BBN consistent at 95% CL including variations in other parameters, e.g. spectrum tilt)
Higher Peaks
Radiation and Dark Matter

- **Radiation domination:** potential wells created by CMB itself
- **Pressure support** $\Rightarrow$ potential decay $\Rightarrow$ driving
- **Heights measures when dark matter dominates**
Radiation and Dark Matter

- Radiation domination: potential wells created by CMB itself
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Decay
and
Gravitational Driving
Radiation and Dark Matter

- Radiation domination: potential wells created by CMB itself
- Pressure support $\Rightarrow$ potential decay $\Rightarrow$ driving
- Heights measures when dark matter dominates

Decay and Gravitational Driving
Dark Matter in the Power Spectrum

\[ \Delta T (\mu K) \]

\[ L \]

Low Matter

High Matter

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Damping Tail in the Power Spectrum

- Photon diffusion exponentially damps oscillations
- Calibrate the standard rulers in curvature test
Diffusion Damping

- Diffusion inhibited by baryons
- Random walk length scale depends on time to diffuse: horizon scale at recombination

Coulomb Interactions
Thomson Scattering

Low Baryons
High Baryons
Damping Consistency Tests

- Additional measure of baryons and dark matter
Beyond the Peaks
Degeneracies

• Multiple cosmological parameters have (nearly) degenerate effects on the power spectrum

• Example: reionization and gravity waves
Polarization

- Thomson of *quadrupole temperature anisotropy*
- Linear polarization:
Polarization Generation

- Quadrupole anisotropies generated in optically thin regime
- Anisotropies <10% polarized
Polarization Patterns

- Pattern reflects the projection of quadrupole anisotropies
- Three types: density, vorticity, gravity waves
- Potential to isolate gravity waves

Density $m=0$

Vorticity $m=1$

Gravity Waves $m=2$
Secondary Anisotropies

- CMB photons traverse the large-scale structure of the universe
- Scattering (≈few%), gravitational redshift, lensing
Power in Secondaries

- **Gravitational**
  ISW (redshift) Effect
  Weak Lensing

- **Scattering**
  Doppler Effect
  Vishniac Effect
  Kinetic SZ Effect
  Patchy Reionization
  Thermal SZ Effect

- **Separation**
  Arcminute Scales
  Spectrum
  Non-Gaussianity
Summary

• Age of precision cosmology

• Sound waves: inflationary/initial perturbations

• First peak nailed: (nearly?) flat universe (11 Gyr young universe preferred)

• Second peak constrained: baryonic dark matter (50% more baryons preferred)

• Degeneracies and ambiguities:
  dark energy: complementary measures
  dark matter: higher peaks
  gravity waves: polarization
  reionization: polarization & secondaries