The Outtakes

- CMB Transfer Function
- Testing Inflation
- Weighing Neutrinos
- Decaying Neutrinos
- Testing $\Lambda$
- Testing Quintessence
- Polarization Sensitivity
- SDSS Complementarity
- Secondary Anisotropies
- Doppler Effect
- Vishniac Effect
- Patchy Reionization
- Sunyaev-Zel'dovich Effect
- Rees-Sciama & Lensing

- Foregrounds
- Doppler Peaks?
- SNIa Complementarity
- Polarization Primer
- Gamma Approximation
- ISW Effect

Back to Talk
Doppler Effect

- Relative velocity of fluid and observer
- Extrema of oscillations are turning points or velocity zero points
- Velocity $\pi/2$ out of phase with temperature
Doppler Effect

- Relative velocity of fluid and observer
- Extrema of oscillations are turning points or velocity zero points
- Velocity $\pi/2$ out of phase with temperature
- Zero point not shifted by baryon drag
- Increased baryon inertia decreases effect
  \[ m_{\text{eff}} V^2 = \text{const.} \quad V \propto m_{\text{eff}}^{-1/2} = (1+R)^{-1/2} \]

**No baryons**

**Baryons**
Doppler Peaks?

- Doppler effect has lower amplitude and weak features from projection

![Diagram showing Doppler peaks and non-peak scenarios](image)

\[ j_l(kd)Y_l^0 \]

Temperature peak

\[ (2l+1)\langle\lambda_l|100\rangle \]

Doppler no peak

\[ (2l+1)\langle\lambda_l\rangle_{l}(100) \]

Hu & Sugiyama (1995)
Relative Contributions

Hu & Sugiyama (1995); Hu & White (1997)
Relative Contributions

Hu & Sugiyama (1995); Hu & White (1997)
Projection into Angular Peaks

- Peaks in spatial power spectrum
- Projection on sphere
- Spherical harmonic decomposition
- Maximum power at $l = kd$
- Extended tail to $l \ll kd$
- Described by spherical bessel function $j_l(kd)$

$\text{Bond & Efstathiou (1987)}$  $\text{Hu & Sugiyama (1995); Hu & White (1997)}$
Projection into Angular Peaks

- Peaks in *spatial* power spectrum
- Projection on *sphere*
- Spherical harmonic decomposition

- Maximum power at $l = kd$
- Extended tail to $l \ll kd$
- 2D Transfer Function $T^2(k,l) \sim (2l+1)^2 [\Delta T/T]^2 j_l^2(kd)$

Hu & Sugiyama (1995)
Measuring the Potential

- Remove smooth damping (independent of perturbations)
- Measure relative peak heights
- Relate to $R\Psi$ at last scattering
- Compare with large scale structure $\Psi$ today
- Residual is smooth potential envelope and measures matter–radiation ratio

Hu & White (1996)
Uses of Acoustic Oscillations

• Distinct features
• Presence/absence unmistakable
• Sensitive to background parameters through fluid parameters
• Sensitive to perturbations through gravitational potential wells which later form structure

• Robust measures of

Angular diameter distance (curvature)
Baryon–photon ratio
Uses of Baryon Drag

- Measures baryon–photon ratio at last scattering + $z_{\text{last scattering}} + T_{\text{CMB}}$ → $\Omega_b h^2$

- Measures potential wells at last scattering (compare with large–scale structure today)

- Removes phase ambiguity by distinguishing compression from rarefaction peaks (separates inflation from causal seed models)
Uses of Damping

• Sensitive to thermal history and baryon content

• Independent of (robust to changes in) perturbation spectrum

• Robust physical scale for angular diameter distance test
  \((\Omega_K, \Omega_\Lambda)\)
Integrated Sachs–Wolfe Effect

- Potential redshift: $g_{00} = -(1 + \Psi)^2 \delta_{ij}$

Kofman & Starobinskii (1985)  
Hu & Sugiyama (1994)
Integrated Sachs–Wolfe Effect

- Potential redshift: \( g_{00} = -(1 + \Psi)^2 \delta_{ij} \)
- Perturbed cosmological redshift
  \[ g_{ij} = a^2 (1 + \Psi)^2 \delta_{ij} \]
  \[ \delta T/T = -\delta a/a = \Psi \]

Kofman & Starobinskii (1985)  
Hu & Sugiyama (1994)
Integrated Sachs–Wolfe Effect

- Potential redshift: \( g_{00} = -(1+\Psi)^2 \delta_{ij} \)
- Perturbed cosmological redshift
  \( g_{ij} = a^2 (1+\Psi)^2 \delta_{ij} \)
  \( \delta T/T = -\delta a/a = \Psi \)
- Time–varying potential
  - Rapid compared with \( \lambda/c \)
  \( \delta T/T = -2\Delta\Psi \)
  - Slow compared with \( \lambda/c \)
  redshift–blueshift cancel
- Imprint characteristic time scale of decay in angular spectrum

\( \text{Kofman & Starobinskii (1985)} \quad \text{Hu & Sugiyama (1994)} \)
Testing Inflation / Initial Conditions

- Superluminal expansion (inflation) required to generate superhorizon curvature (density) perturbations.
- Else perturbations are isocurvature initially with matter moving causally.
- Curvature (potential) perturbations drive acoustic oscillations.
- Ratio of peak locations.
- Harmonic series: curvature 1:2:3... isocurvature 1:3:5...
Testing Inflation / Initial Conditions

- Superluminal expansion (inflation) required to generate superhorizon curvature (density) perturbations

- Else perturbations are isocurvature initially with matter moving causally

- Curvature (potential) perturbations drive acoustic oscillations

- Ratio of peak locations

- Harmonic series:
  - curvature 1:2:3...
  - isocurvature 1:3:5...

Hu & White (1996)
Weighing Neutrinos

- **Massive neutrinos** suppress power strongly on small scales
  \[ \frac{\Delta P}{P} \approx -8 \Omega_\nu/\Omega_m \]: well modeled by \[ c_{\text{eff}}^2 = w_g, \quad c_{\text{vis}}^2 = w_g, \quad w_g : 1/3 \rightarrow 1 \]

- **Degenerate** with other effects [tilt \( n \), \( \Omega_m h^2 \ldots \)]

- CMB signal small but breaks degeneracies

- 2\(\sigma\) Detection: \(0.3\)eV [Map (pol) + SDSS]

---

**Power Suppression**

\[ \begin{array}{c}
\Omega_\nu h^2 = m_\nu/94\text{eV} \\
SDSS: m_\nu = 0 \text{eV} \\
m_\nu = 1 \text{eV}
\end{array} \]

**Complementarity**

Hu, Eisenstein, & Tegmark (1998); Eisenstein, Hu & Tegmark (1998)
Cosmology and the Neutrino Anomalies

Hata (1998)
Cosmology and the Neutrino Anomalies

Hata (1998)
Hu, Eisenstein & Tegmark (1998)
Cosmology and the Neutrino Anomalies

Hata (1998)
Hu, Eisenstein & Tegmark (1998)
Hu & Tegmark (1998)
Decaying Dark Matter

- Example: relativistic matter goes non-relativistic, decays back into radiation
- Model decay and decay products as a single component of dark matter
- Novel consequences: scale-invariant curvature perturbation from scale-invariant isocurvature perturbations

Hu (1998)
Testing $\Lambda$

- If $w_g < 0$, GDM has no effect on acoustic dynamics $\rightarrow (k_{\text{peaks}}, \text{heights})$ independent of $w_g$, $\Omega_g$, $c_{\text{eff}}$, $c_{\text{vis}}$

- CMB sensitive to GDM/$\Lambda$ mainly through angular diameter distance $[d_A = f(w_g, \Omega_g...)]$

Hu, Eisenstein, Tegmark & White (1998)
Testing $\Lambda$

- If $w_g < 0$, GDM has no effect on acoustic dynamics $\rightarrow (k_{\text{peaks}}, \text{heights})$ independent of $w_g$, $\Omega_g$, $c_{\text{eff}}$, $c_{\text{vis}}$

- **CMB** sensitive to GDM/$\Lambda$ mainly through angular diameter distance $[d_A = f(w_g, \Omega_g,...)]$

- **Galaxy surveys** determines $h$
- CMB determines $\Omega_m h^2 \rightarrow \Omega_m$
- Flatness $\Omega_g = 1 - \Omega_m$

Hu, Eisenstein, Tegmark & White (1998)
Testing $\Lambda$

- If $w_g < 0$, GDM has no effect on acoustic dynamics $\rightarrow (k_{\text{peaks}}, \text{heights})$ independent of $w_g, \Omega_g, c_{\text{eff}}, c_{\text{vis}}$

- CMB sensitive to GDM/$\Lambda$ mainly through angular diameter distance $[d_A = f(w_g, \Omega_g)]$

- Galaxy surveys determines $h$

- CMB determines $\Omega_m h^2 \rightarrow \Omega_m$

- Flatness $\Omega_g = 1 - \Omega_m$

- SNIa determines luminosity distance $[d_L = f(w_g, \Omega_g)]$

Hu, Eisenstein, Tegmark & White (1998)
Testing $\Lambda$

- If $w_g < 0$, GDM has no effect on acoustic dynamics $\rightarrow (k_{\text{peaks}}, \text{heights})$ independent of $w_g, \Omega_g, c_{\text{eff}}, c_{\text{vis}}$

- CMB sensitive to GDM/$\Lambda$ mainly through angular diameter distance $[d_A=f(w_g, \Omega_g...)]$

- Galaxy surveys determines $h$

- CMB determines $\Omega_m h^2 \rightarrow \Omega_m$

- Flatness $\Omega_g = 1 - \Omega_m$

- SNIa determines luminosity distance $[d_L=f(w_g, \Omega_g)]$

Is the Missing Energy a Scalar Field?

• **Scalar Fields** have maximal sound speed \([c_{\text{eff}} = 1, \text{speed of light}]\)

• **CMB+LSS → Lower limit on** \(c_{\text{eff}} > 0.6\) at \(w_g = -1/6\)
  
  \[2.7\sigma: \text{MAP+SDSS; } 7.7\sigma: \text{Planck+SDSS}\]

  [in 10d parameter space, including bias, tensors]

• **Strong constraints for** \(w_g > -1/2\)

Large Scale Structure

\[
P(k) \quad c_{\text{eff}}^2 = 0 \quad 1/6 \quad 1/6 \quad 1 \quad \text{scalar fields}
\]

\[
k (h \text{ Mpc}^{-1})
\]

CMB Anisotropies

\[
\text{Power } (\times 10^{-10}) \quad c_{\text{eff}}^2 = 0 \quad 1/6 \quad 1/6 \quad 1 \quad \text{scalar fields}
\]

\[
l
\]

Hu, Eisenstein, Tegmark & White (1998)
Polarization from Thomson Scattering

- Thomson scattering of anisotropic radiation → linear polarization
- Polarization aligned with cold lobe of the quadrupole anisotropy
Perturbations & Their Quadrupoles

- Orientation of quadrupole relative to wave ($\mathbf{k}$) determines pattern
- Scalars (density) $m=0$
- Vectors (vorticity) $m=\pm 1$
- Tensors (gravity waves) $m=\pm 2$

Hu & White (1997)
Polarization Patterns

Scalars

Vectors

Tensors
Electric & Magnetic Patterns

- **Global view**: behavior under parity
- **Local view**: alignment of principle vs. polarization axes

Kamionkowski, Kosowski, Stebbins (1997)
Zaldarriaga & Seljak (1997)
Hu & White (1997)
Patterns and Perturbation Types

- **Amplitude** modulated by plane wave → **Principle axis**
- **Direction** determined by perturbation type → **Polarization axis**

**Polarization Pattern**

<table>
<thead>
<tr>
<th>Scalars</th>
<th>Vectors</th>
<th>Tensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>π/2</td>
<td>θ</td>
<td>π/2</td>
</tr>
</tbody>
</table>

**Multipole Power**

- B/E=0
- B/E=6
- B/E=8/13

Kamionkowski, Kosowski, Stebbins (1997); Zaldarriaga & Seljak (1997); Hu & White (1997)
Polarization Raw Sensitivity

$\Delta T$ (µK) vs. $l$
SDSS: Improving Parameter Estimation

**MAP (no pol)**

- $h$: 1.3
- $\Omega_m$: 1.4
- $\Omega_\Lambda$: 1.1
- $\Omega_K$: 0.31

**MAP (pol)**

- $h$: 0.23
- $\Omega_m$: 0.25
- $\Omega_\Lambda$: 0.20
- $\Omega_K$: 0.057

**MAP+SDSS (pol, 0.2 h Mpc$^{-1}$)**

- $h$: 0.012
- $\Omega_m$: 0.016
- $\Omega_\Lambda$: 0.024
- $\Omega_K$: 0.011

Relative Errors

**Classical Cosmology**

Eisenstein, Hu & Tegmark (1998)
Supernovae Type Ia
July 1998

Garnavich et al. (1998); Riess et al. (1998); Perlmutter et al. (1998)
Figure: Hu, Eisenstein, Tegmark, White (1998)
Supernovae Type Ia, CMB & LSS Projection

### SDSS: Improving Parameter Estimation

![Graph showing relative errors for various parameters](SDSS_Graph.png)

**Parameters**
- $h$
- $\Omega_m$
- $\Omega_L$
- $\Omega_K$
- $\Omega_m h^2$
- $\Omega_b h^2$
- $\Omega_v h^2$
- $n_s$
- $\alpha$
- $T/S$
- $\log(A)$
- $\tau$

**Relative Errors**
- **MAP (no pol)**
  - $h$: $1.3$, $0.23$, $1.012$
  - $\Omega_m$: $1.4$, $0.25$, $1.016$
  - $\Omega_L$: $1.1$, $0.20$, $0.024$
  - $\Omega_K$: $0.31$, $0.057$, $0.011$
  - $\Omega_m h^2$: $0.029$, $0.015$, $0.0082$
  - $\Omega_b h^2$: $0.0027$, $0.0013$, $0.0008$
  - $\Omega_v h^2$: $0.0094$, $0.0063$, $0.0019$
  - $n_s$: $0.14$, $0.094$, $0.051$
  - $\alpha$: $0.30$, $0.019$, $0.013$
  - $T/S$: $0.48$, $0.19$, $0.15$
  - $\log(A)$: $1.3$, $0.36$, $0.28$
  - $\tau$: $0.69$, $0.024$

**MAP (pol)**

**MAP+SDSS (pol, 0.2hMpc$^{-1}$)**

**Eisenstein, Hu & Tegmark (1998)**
Secondary Anisotropies

- Temperature and polarization anisotropies imprinted in the CMB after $z=1000$
- Rescattering Effects
  - Linear Doppler Effect (cancelled)
  - Modulated Doppler Effects (non-linear)
    - by linear density perturbations $\rightarrow$ Ostriker–Vishniac Effect
    - by ionization fraction $\rightarrow$ Inhomogeneous Reionization
    - by clusters $\rightarrow$ thermal & kinetic Sunyaev–Zel'dovich Effects
- Gravitational Effects
  - Gravitational Redshifts
    - by cessation of linear growth $\rightarrow$ Integrated Sachs–Wolfe Effect
    - by non-linear growth $\rightarrow$ Rees–Sciama Effect
  - Gravitational Lensing
Cancellation of the Linear Effect

- e-velocity
- redshifted $\gamma$
- blueshifted $\gamma$
- overdensity

Observer

Last Scattering Surface

Cancellation
Modulated Doppler Effect

Observer

Last Scattering Surface

e- velocity
overdensity, ionization patch, cluster...

unscattered $\gamma$

blueshifted $\gamma$
Ostriker–Vishniac Effect

Hu & White (1996)
Patchy Reionization

Aghanim et al. (1996)

Knox, Scoccimarro & Dodelson (1998)

Gruzinov & Hu (1998)

$\ell(\ell + 1)c_\ell / 2\pi$ ($\times 10^{-10}$)

$\ell$

$10^2$ $10^3$ $10^4$

$10^{-15}$ $10^{-14}$ $10^{-13}$ $10^{-12}$ $10^{-11}$ $10^{-10}$ $10^{-9}$

SCDM $\sigma_8 = 1.2$
Thermal SZ Effect

Persi et al. (1995)

Atrio–Barandela & Muecket (1998)
Rees–Sciama Effect

Gravitational Lensing

Seljak (1996a,b)
Residual Foreground Effects

MAP

Temperature

- dust
- synchrotron
- free-free
- increased noise
- point sources

E-polarization

- total
- increased noise
- synchrotron

B-polarization

- total
- increased noise
- synchrotron

Planck

Temperature

- total
- increased noise
- point sources

E-polarization

- total
- dust
- increased noise
- synchrotron

B-polarization

- total
- dust
- increased noise
- synchroton
Foregrounds & Parameter Estimation

Tegmark, Eisenstein, Hu, de Oliveiera Costa (1999)
Features in the Transfer Function

- Features in the linear transfer function
- Break at sound horizon
- Oscillations at small scales; washed out by nonlinearities

\[ T(k) / T_{BBKS86}(k) \]

\[ T(k) \]

\[ \Omega_m = 0.3, \ h = 0.5, \ \Omega_b / \Omega_0 = 0.3 \]

Eisenstein & Hu (1998)