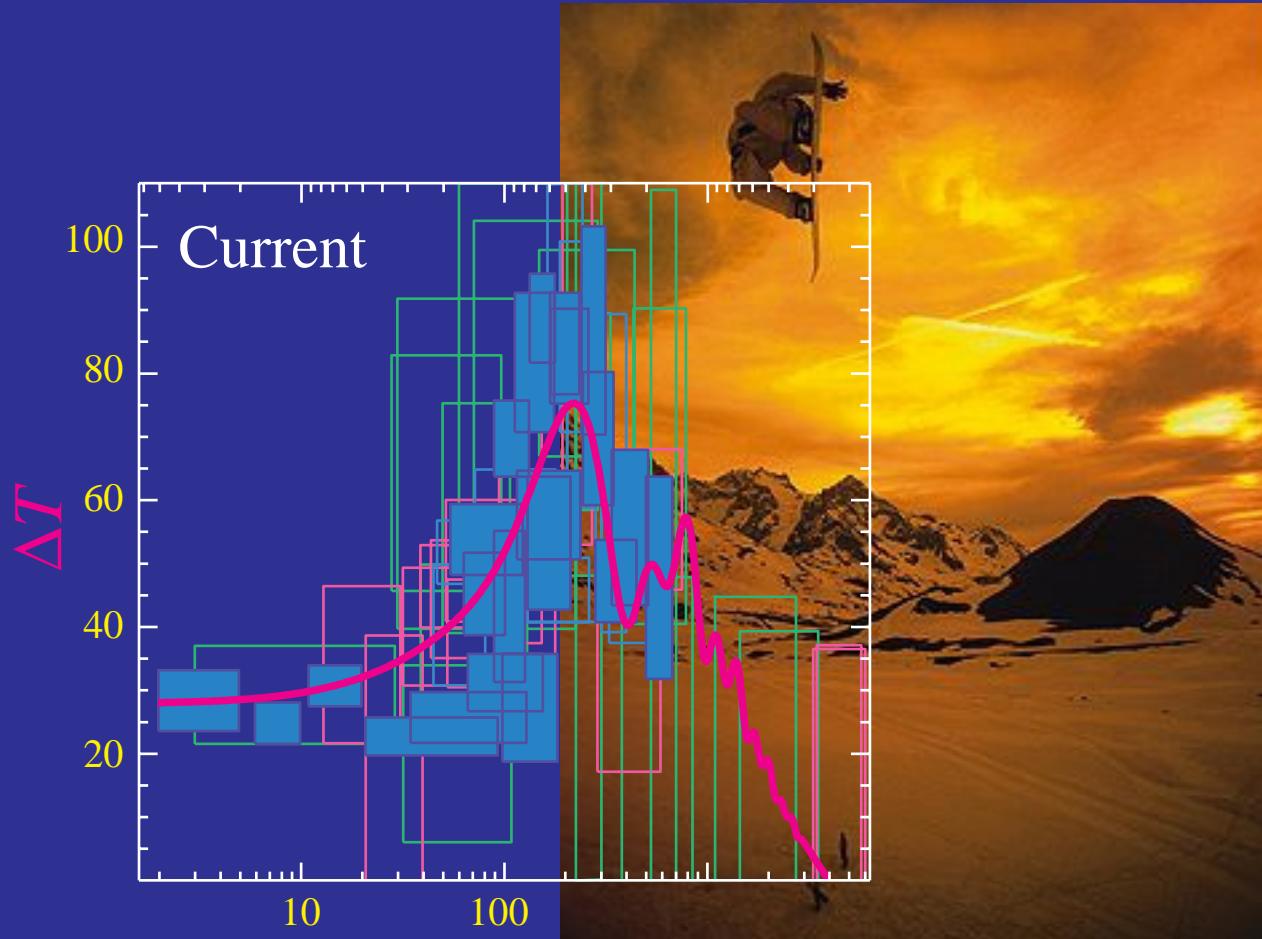


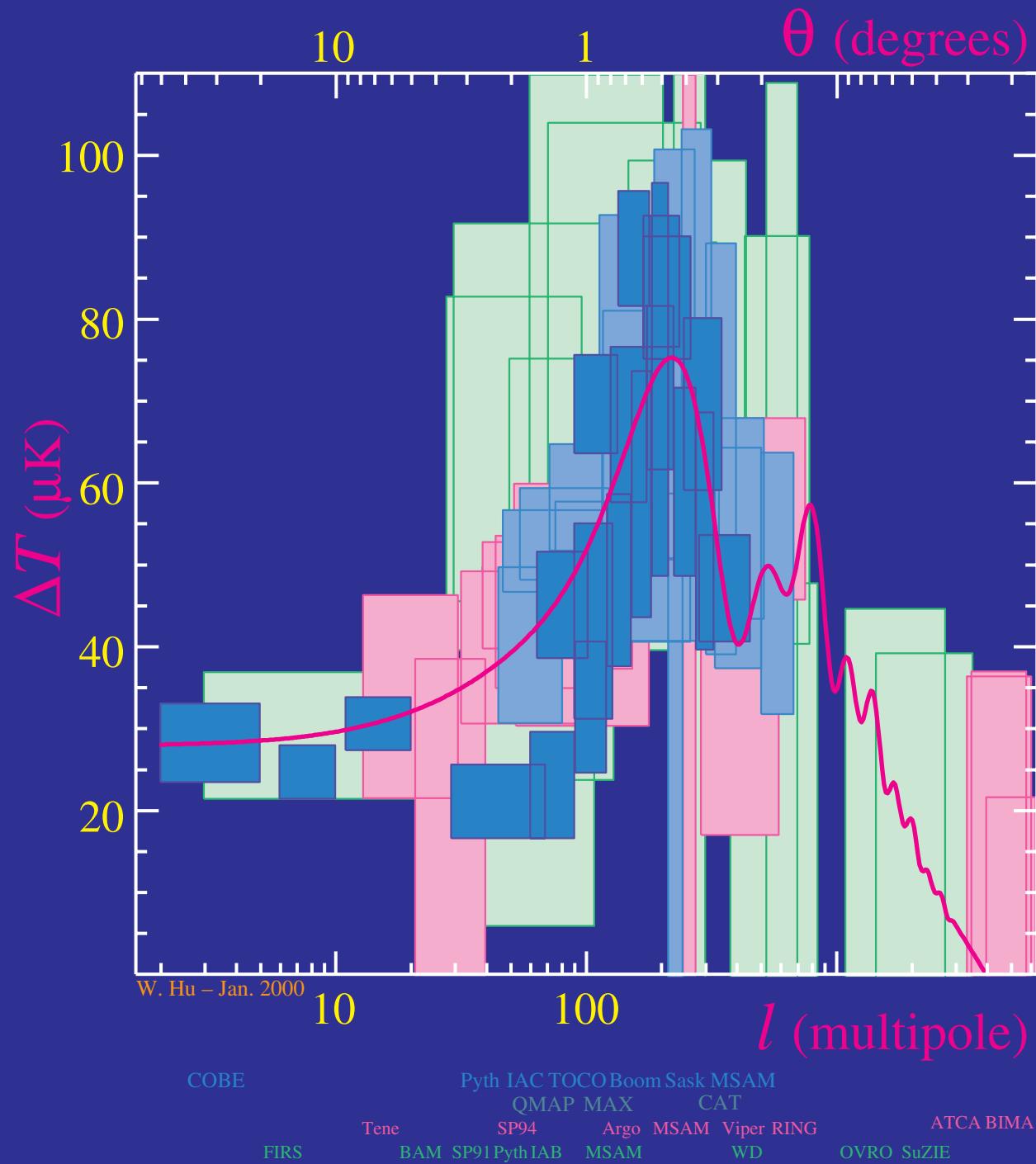
# Physics of CMB Anisotropies



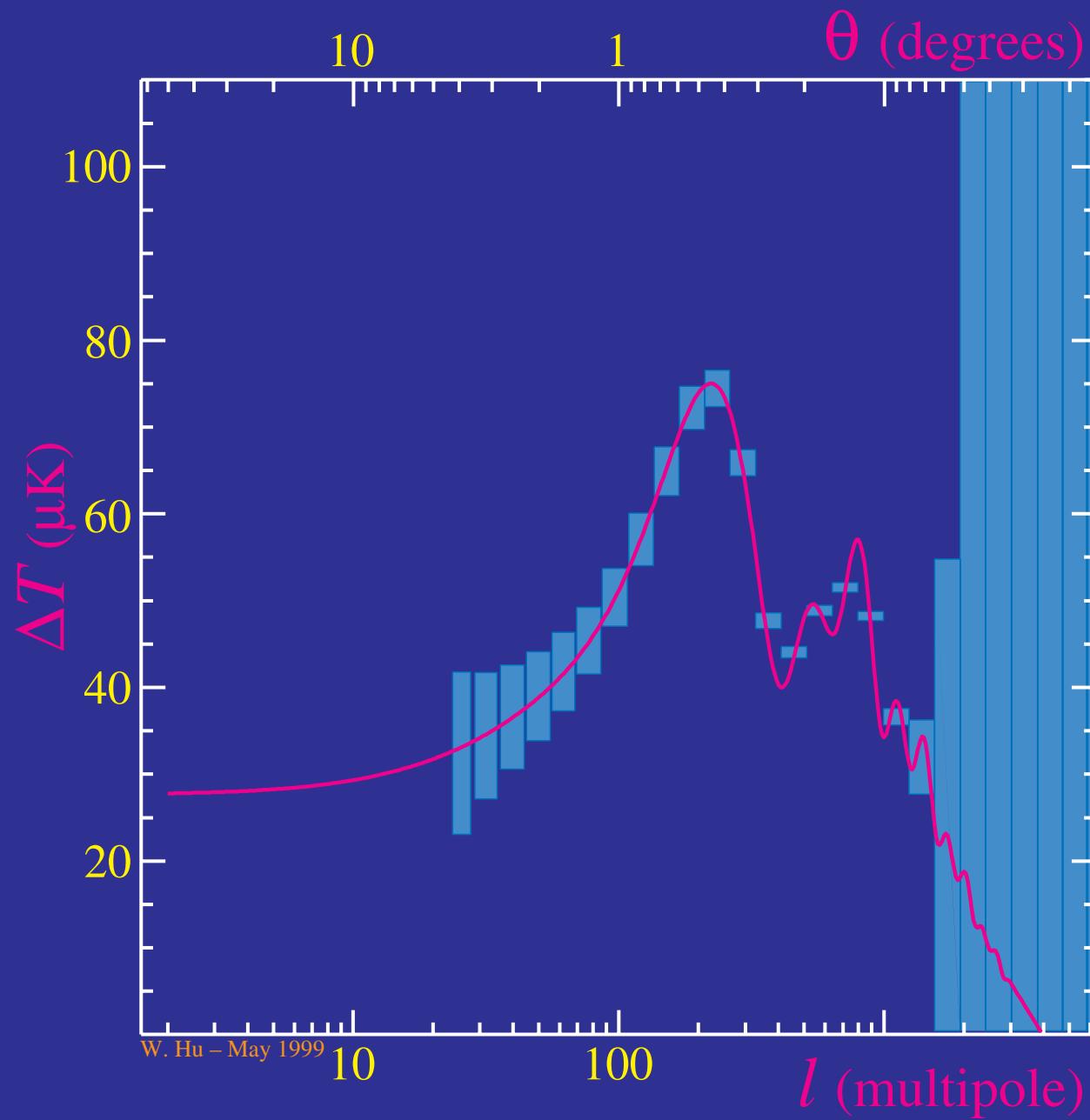
Moriond 2000

Wayne Hu

# Current CMB Quilt



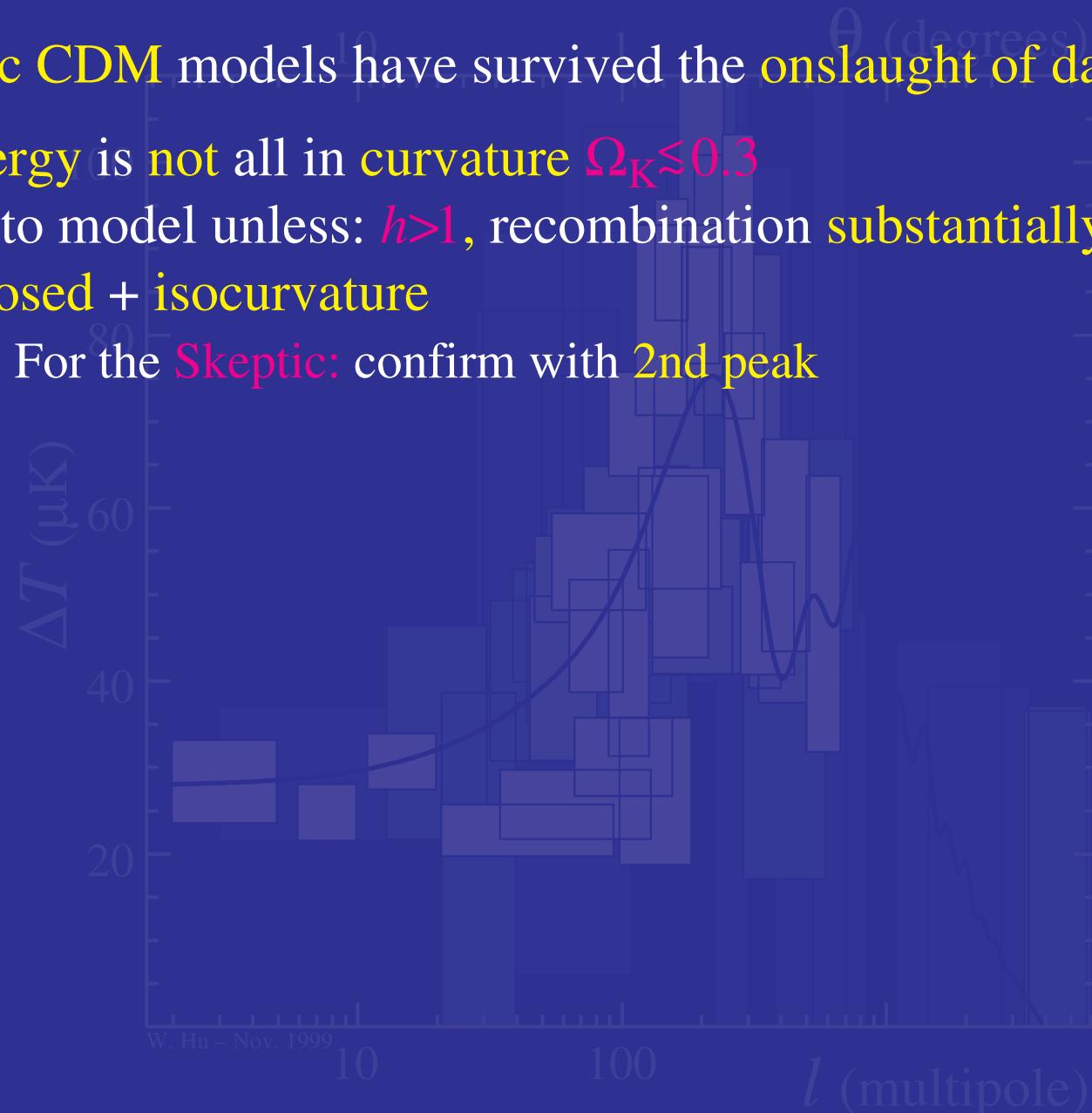
# Projected Boomerang Errors



# What We Have Already Learned

- Adiabatic CDM models have survived the onslaught of data
- Dark energy is not all in curvature  $\Omega_K \lesssim 0.3$   
robust to model unless:  $h > 1$ , recombination substantially delayed,  
or closed + isocurvature

For the Skeptic: confirm with 2nd peak



Lineweaver (1998); Bond & Jaffe (1998); Dodelson & Knox (1999); Tegmark & Zaldarriaga (1999)

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For the **Skeptic**: confirm with 2nd peak; measure with 3rd peak  
Hints of low  $\Omega_m \approx 0.3$  hence a cosmological constant  $\Omega_\Lambda \approx 0.7$   
For the **Skeptic**: confirm with relative peak heights  
Optically thin during reionization  $\tau \leq 0.5$

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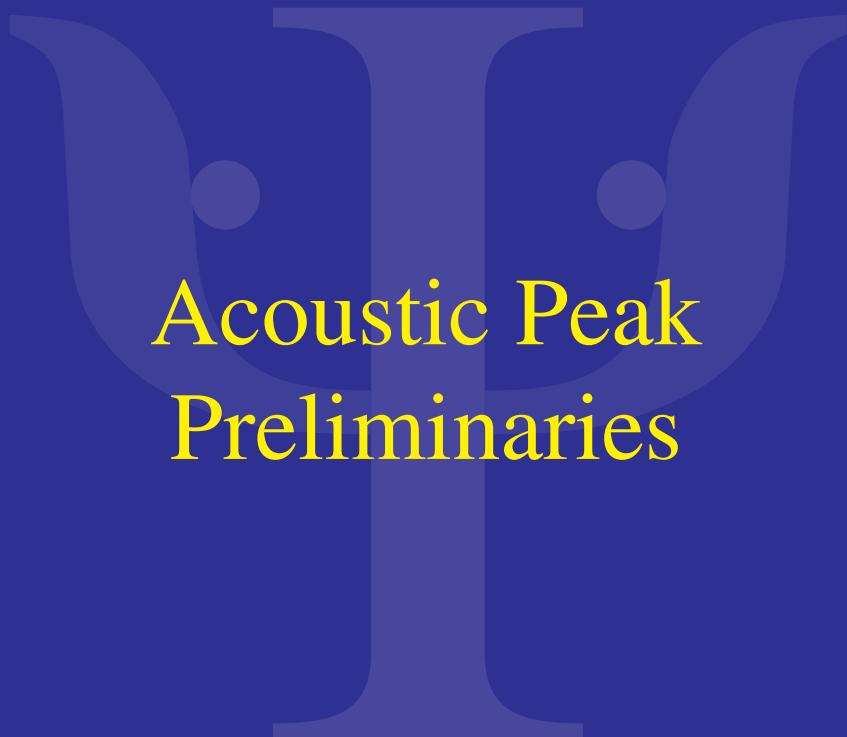
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  - Optically thin during reionization  $\tau \leq 0.5$
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  - For the **Skeptic**: confirm with the polarization
- Consistent with LSS, cluster abundance, SNIa, BBN,  $h$

Lineweaver (1998); Bond & Jaffe (1998); Dodelson & Knox (1999); Tegmark & Zaldarriaga (1999)



# Acoustic Peak Preliminaries

# Thermal History

- $z > 1000$ ;  $T_\gamma > 3000\text{K}$

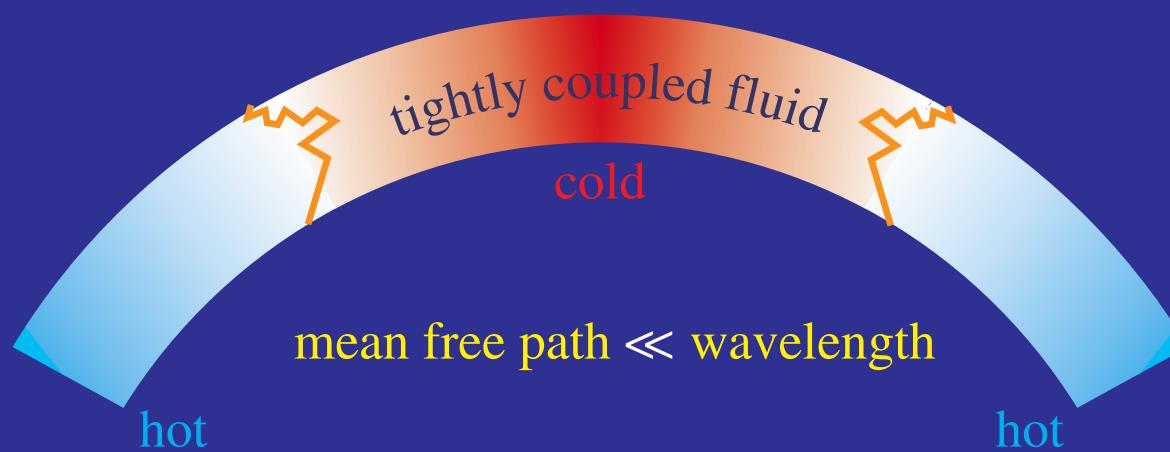
Hydrogen ionized

Free electrons glue photons to baryons



Photon–baryon fluid

Potential wells that later form structure



# Thermal History

- $z > 1000$ ;  $T_\gamma > 3000\text{K}$

Hydrogen ionized

Free electrons glue photons to baryons



Photon–baryon fluid

Potential wells that later form structure

- $z \sim 1000$ ;  $T_\gamma \sim 3000\text{K}$

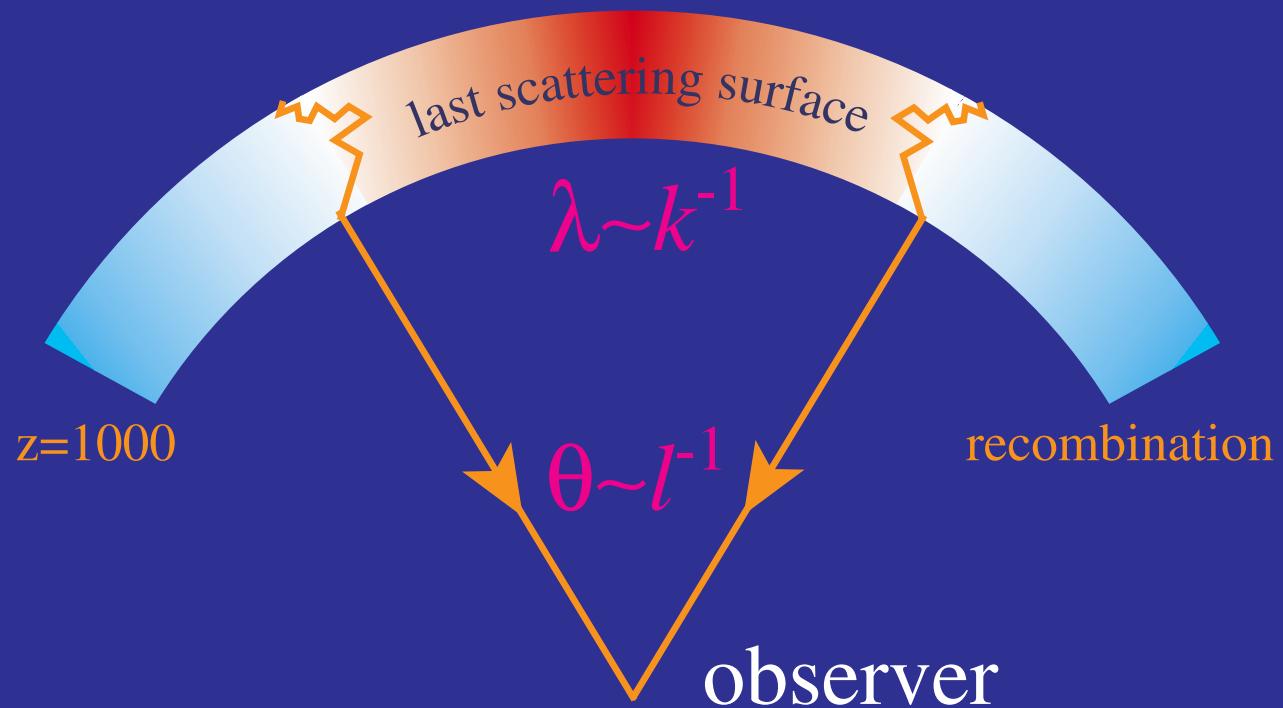
Recombination

Fluid breakdown

- $z < 1000$ ;  $T_\gamma < 3000\text{K}$

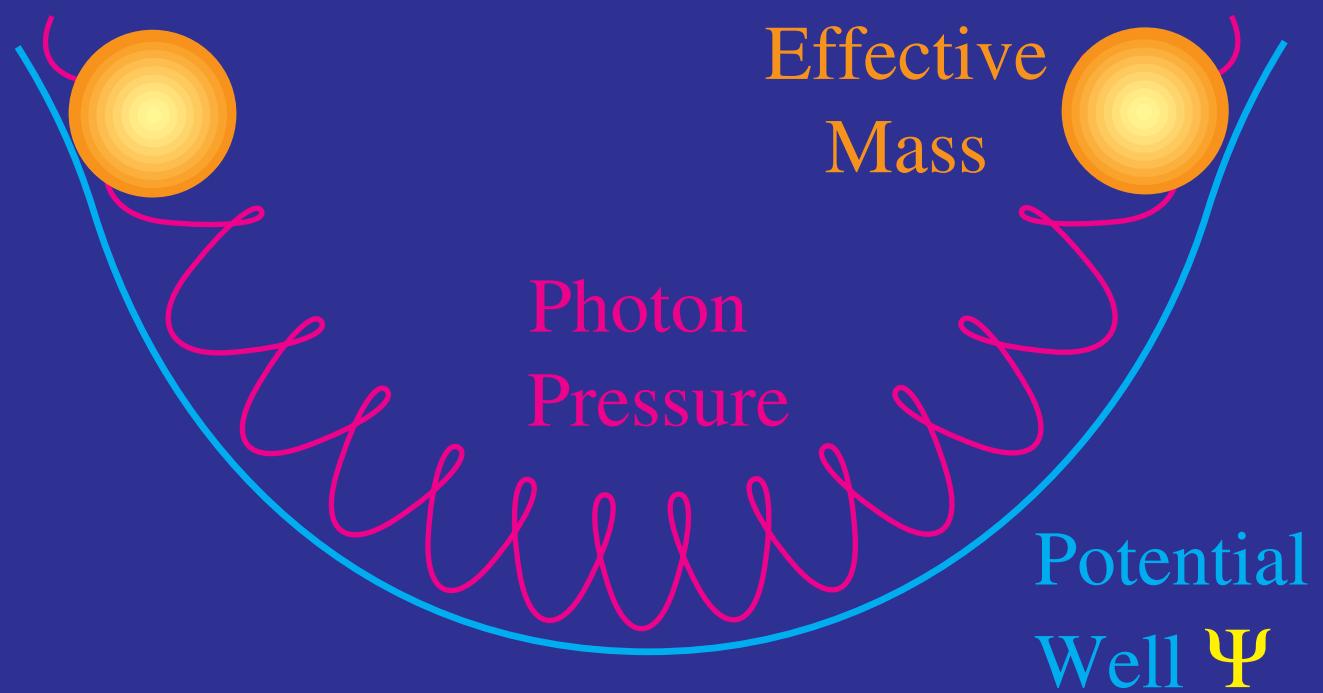
Gravitational redshifts &  
lensing

Reionization; rescattering



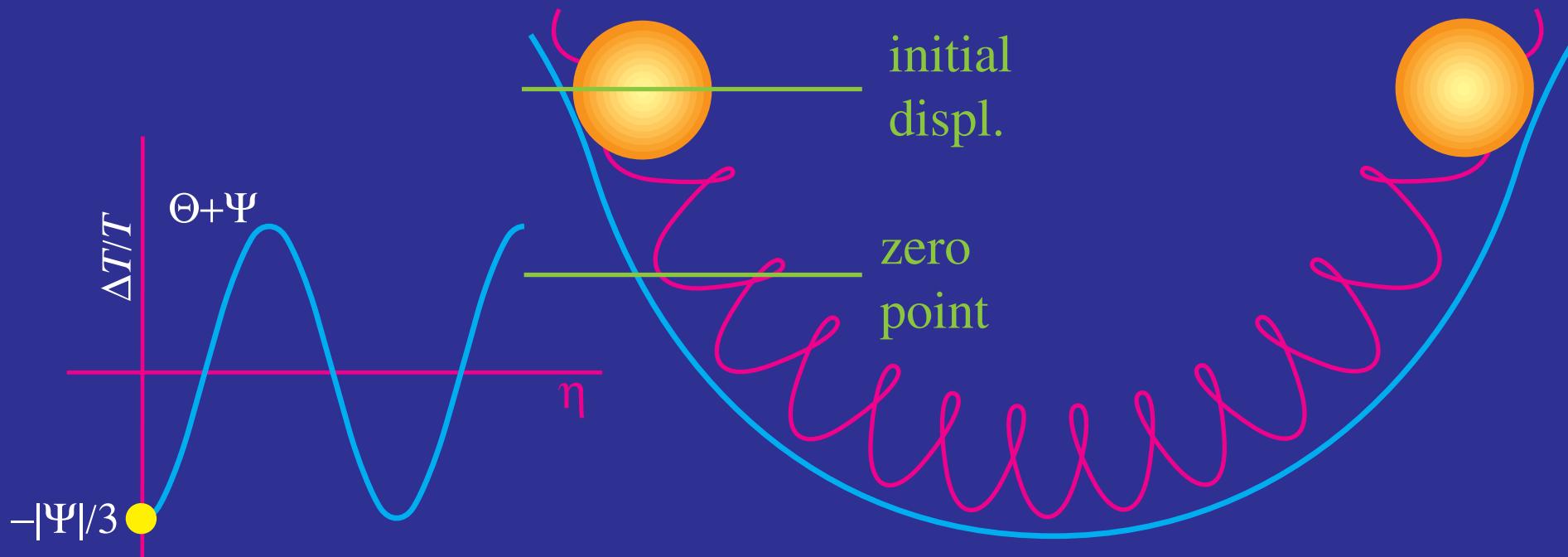
# Acoustic Oscillations

- Photon pressure resists compression in potential wells
- Acoustic oscillations



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 $\Theta \equiv \delta T/T = -\Psi$
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 $\Theta - (-\Psi) = 1/3\Psi$

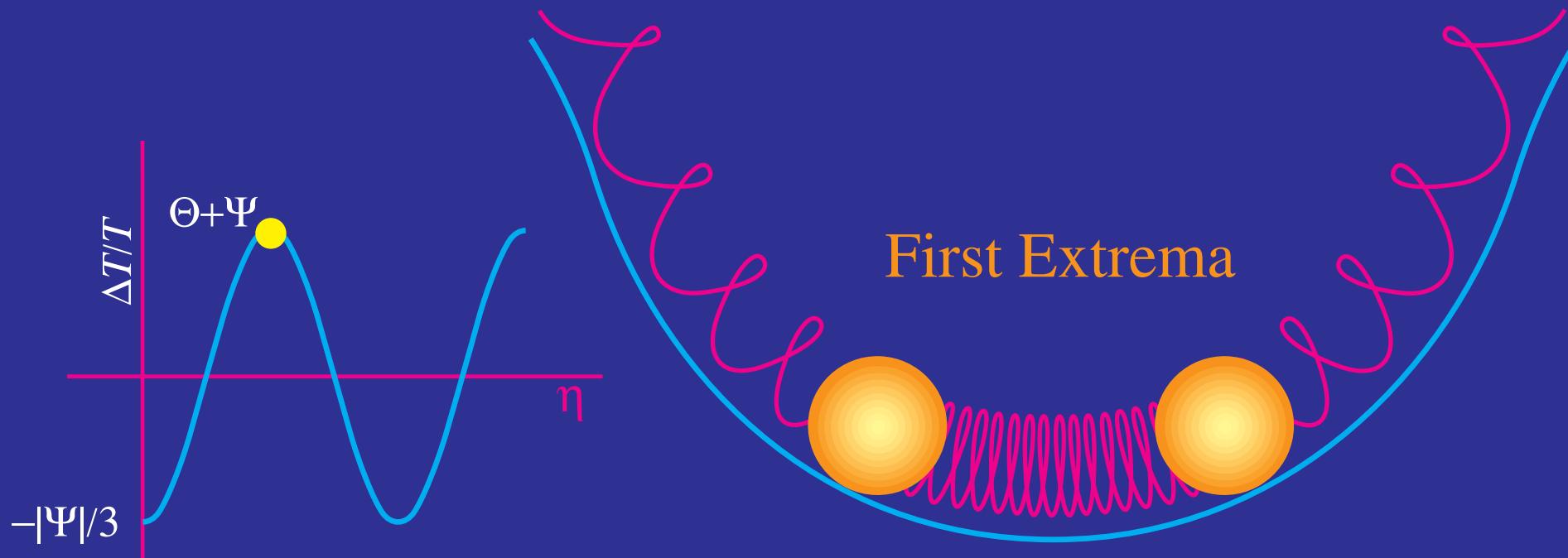


Peebles & Yu (1970)

Hu & Sugiyama (1995)

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Peebles & Yu (1970)

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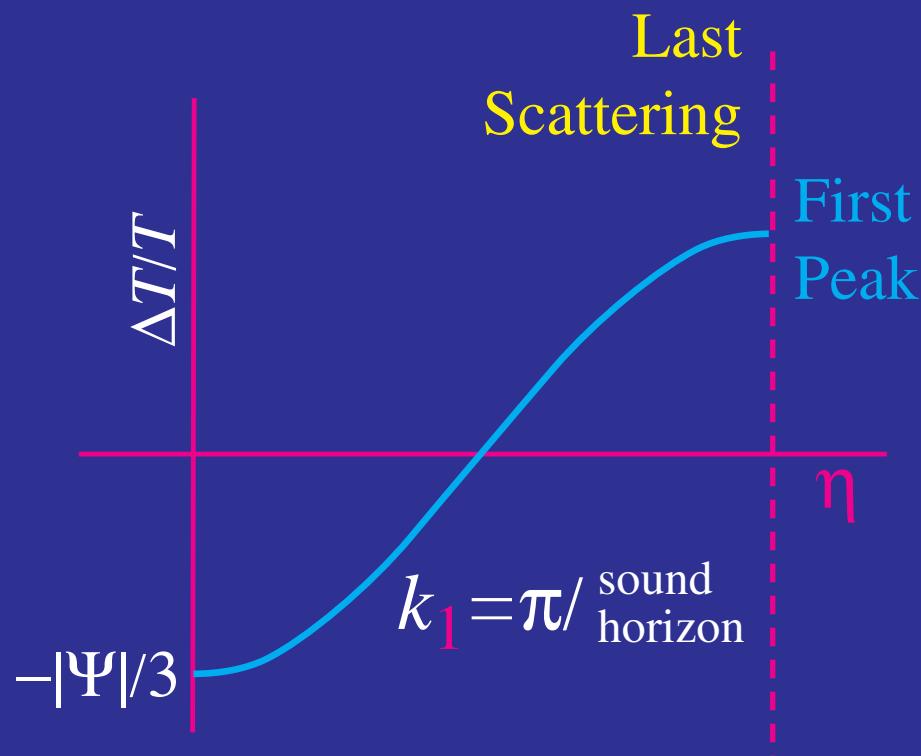


Peebles & Yu (1970)

Hu & Sugiyama (1995)

# Harmonic Peaks

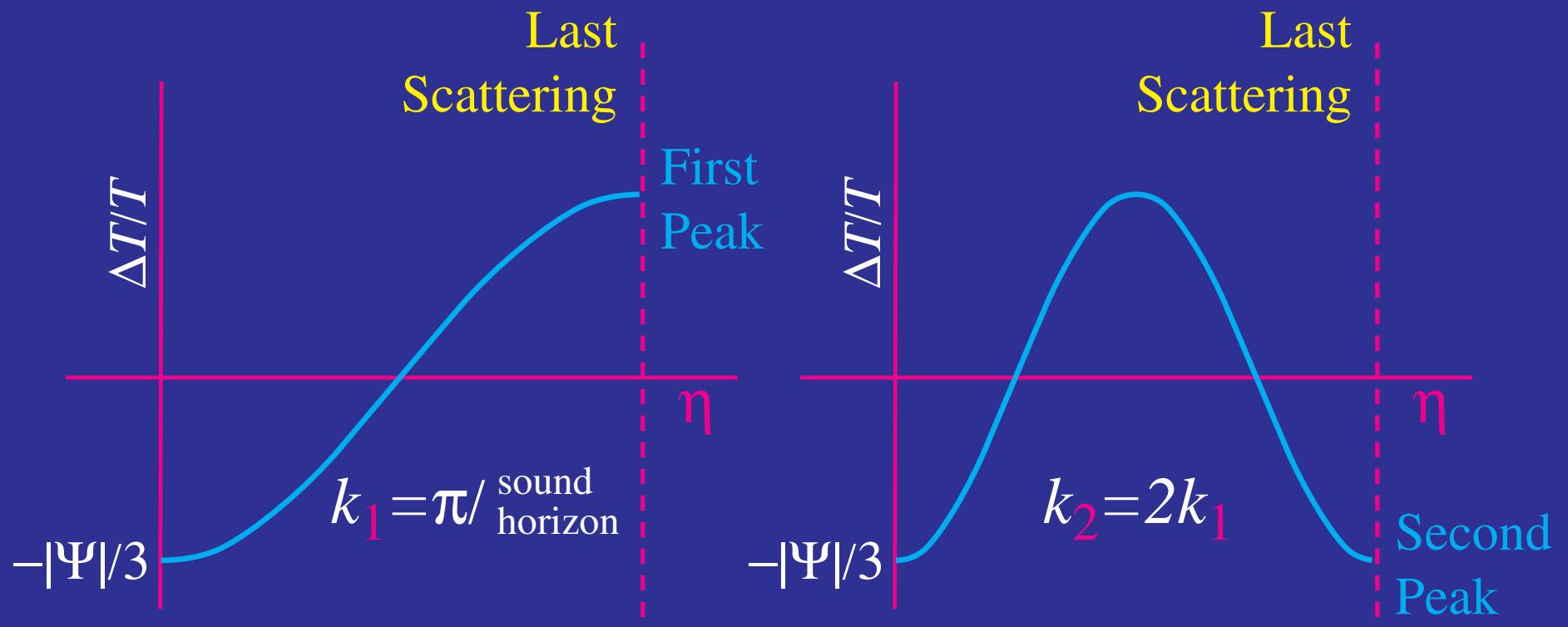
- Oscillations frozen at last scattering
- Wavenumbers at extrema = peaks
- Sound speed  $c_s$



Doroshkevich, Zel'dovich & Sunyaev (1978); Bond & Efstathiou (1984); Hu & Sugiyama (1995)

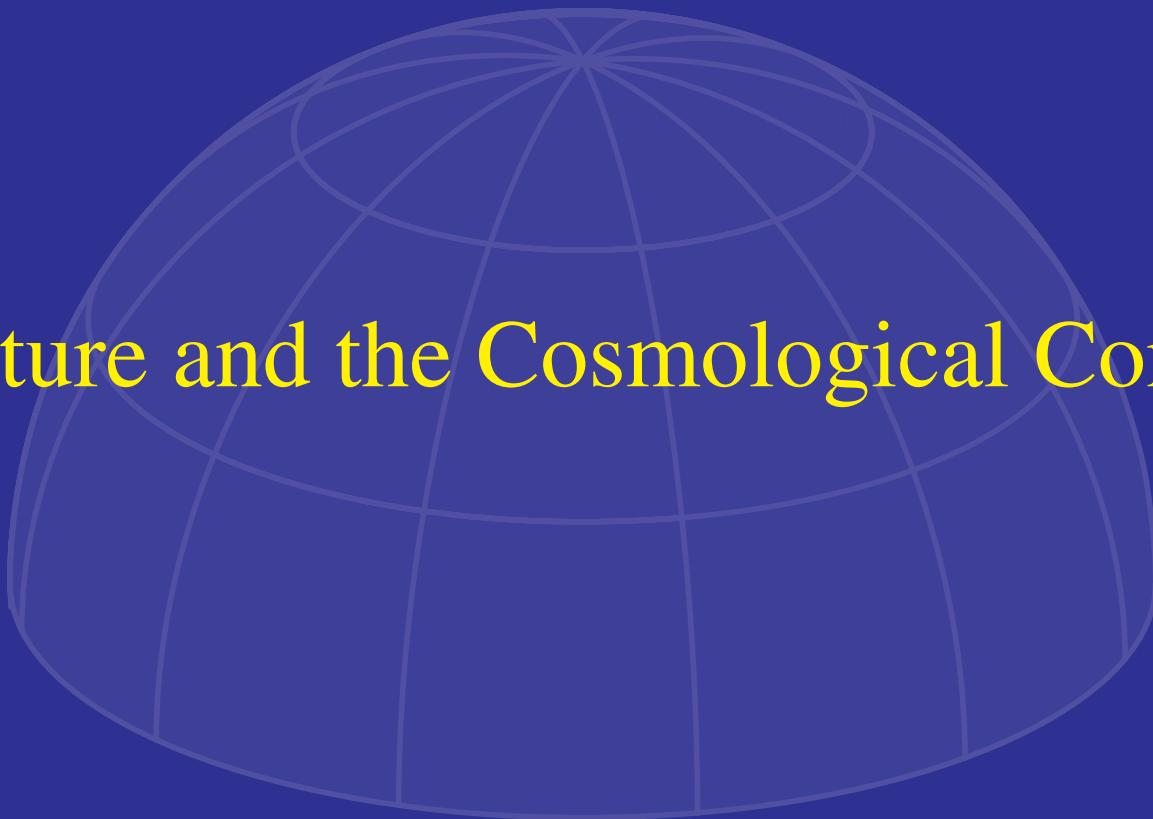
# Harmonic Peaks

- Oscillations frozen at last scattering
- Wavenumbers at extrema = peaks
- Sound speed  $c_s$
- Frequency  $\omega = kc_s$ ; conformal time  $\eta$
- Phase  $\propto k$ ;  $\phi = \int_0^{\text{last scattering}} d\eta \omega = k \text{ sound horizon}$
- Harmonic series in sound horizon  
 $\phi_n = n\pi \rightarrow k_n = n\pi / \text{sound horizon}$



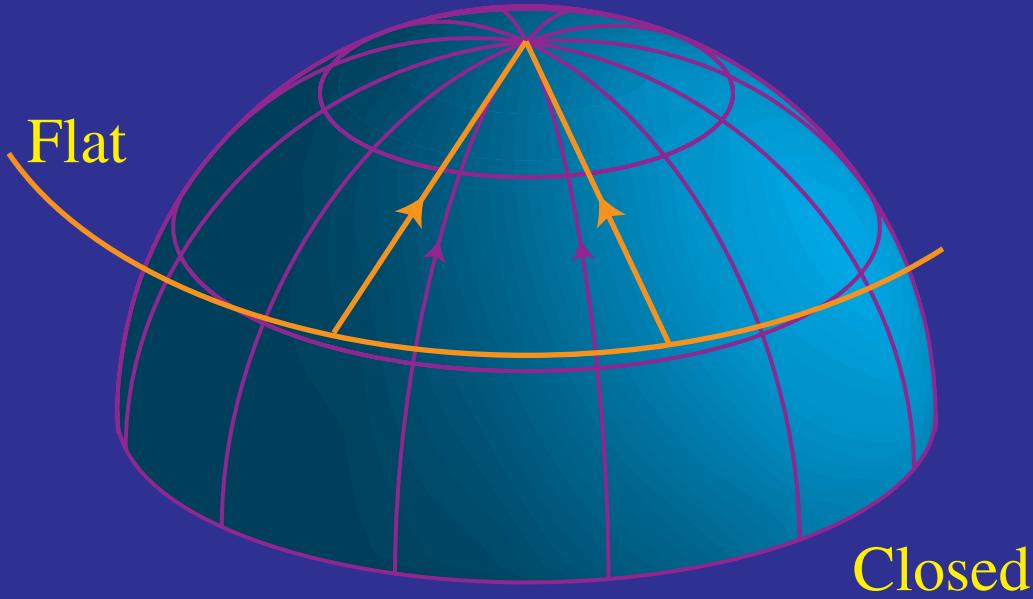
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# Curvature and the Cosmological Constant



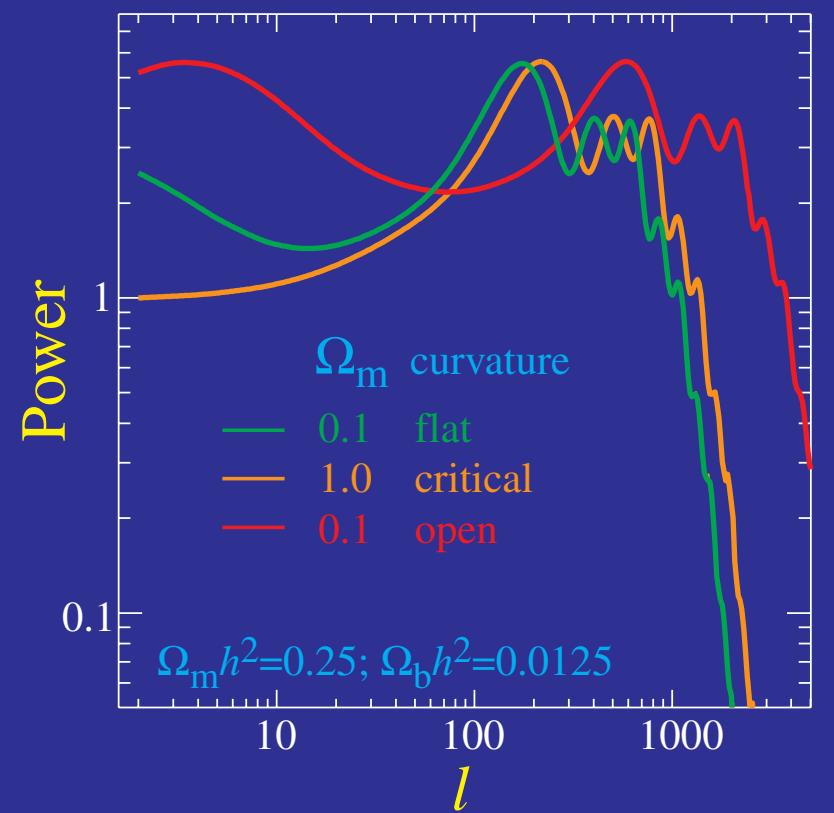
# Angular Diameter Distance

- A Classical Test
  - Standard(ized) comoving ruler
  - Measure angular extent
  - Absolute scale drops out
- Infer curvature

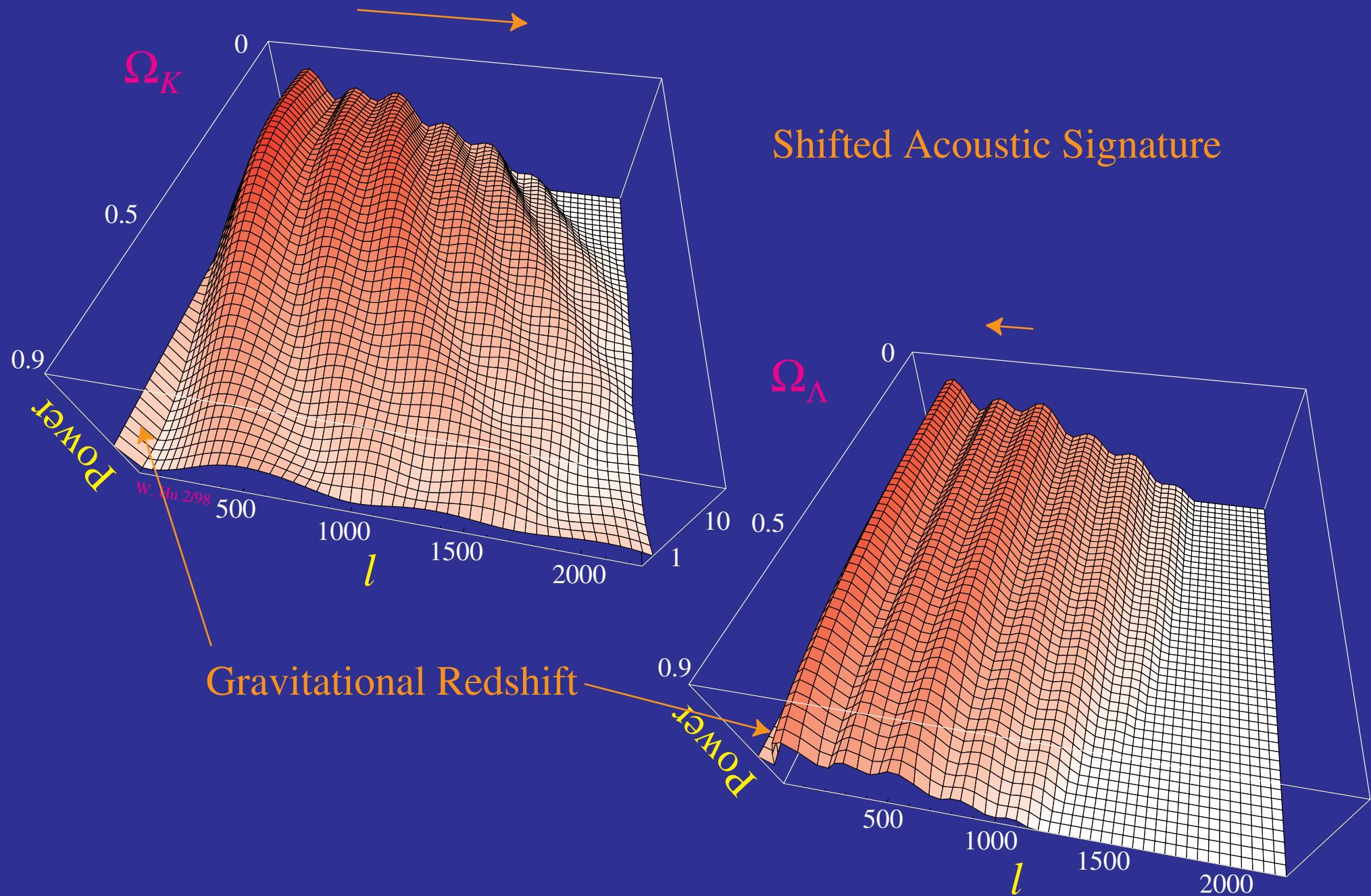


Kamionkowski, Spergel & Sugiyama (1994)  
Hu & White (1996)

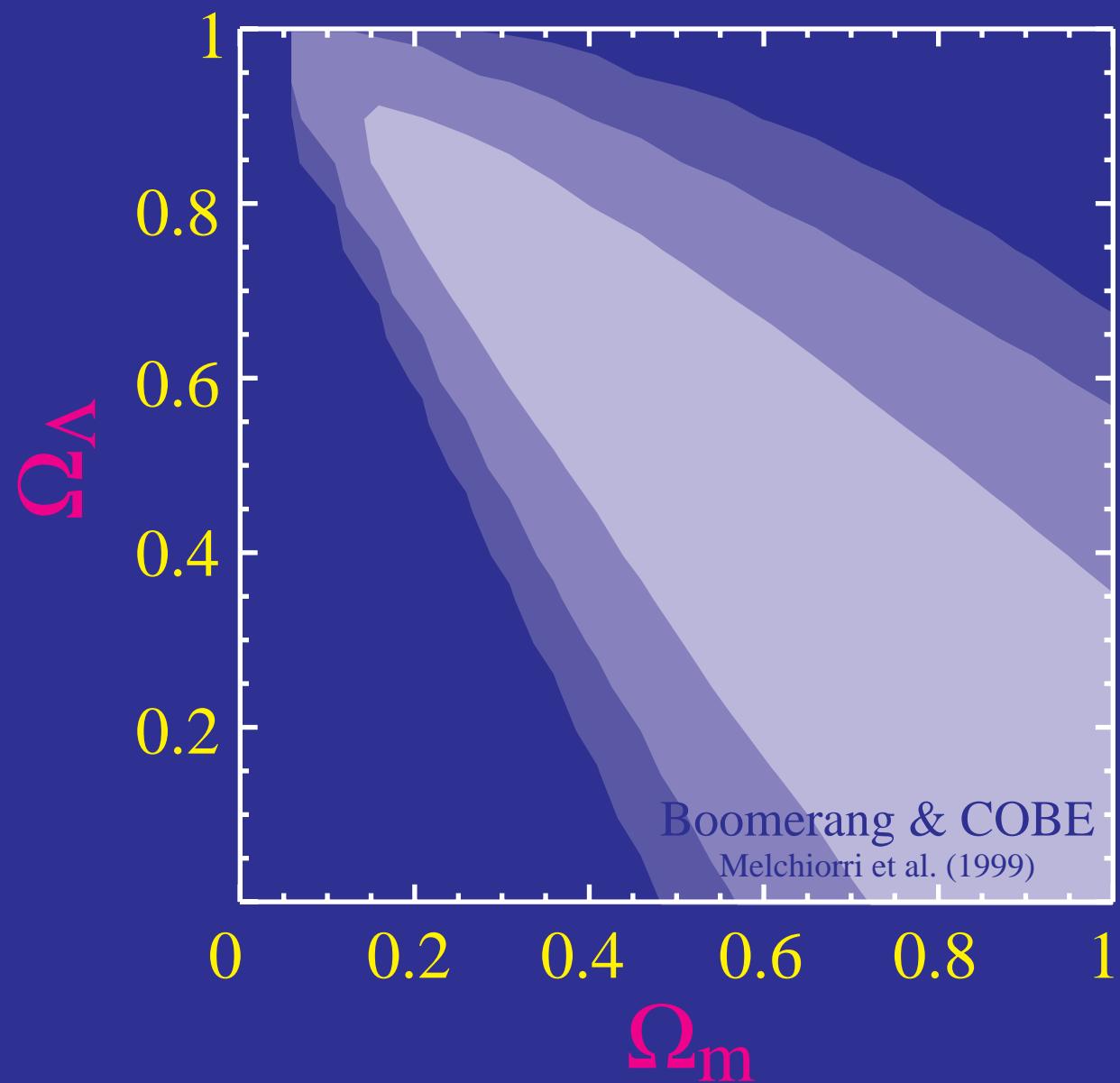
- Upper limit 1st Peak Scale (Horizon)  
Upper limit on Curvature
- Calibrate 2 Physical Scales
  - Sound horizon (peak spacing)  $\Omega_m h^2$  IC's
  - Diffusion scale (damping tail)  $\Omega_b h^2$



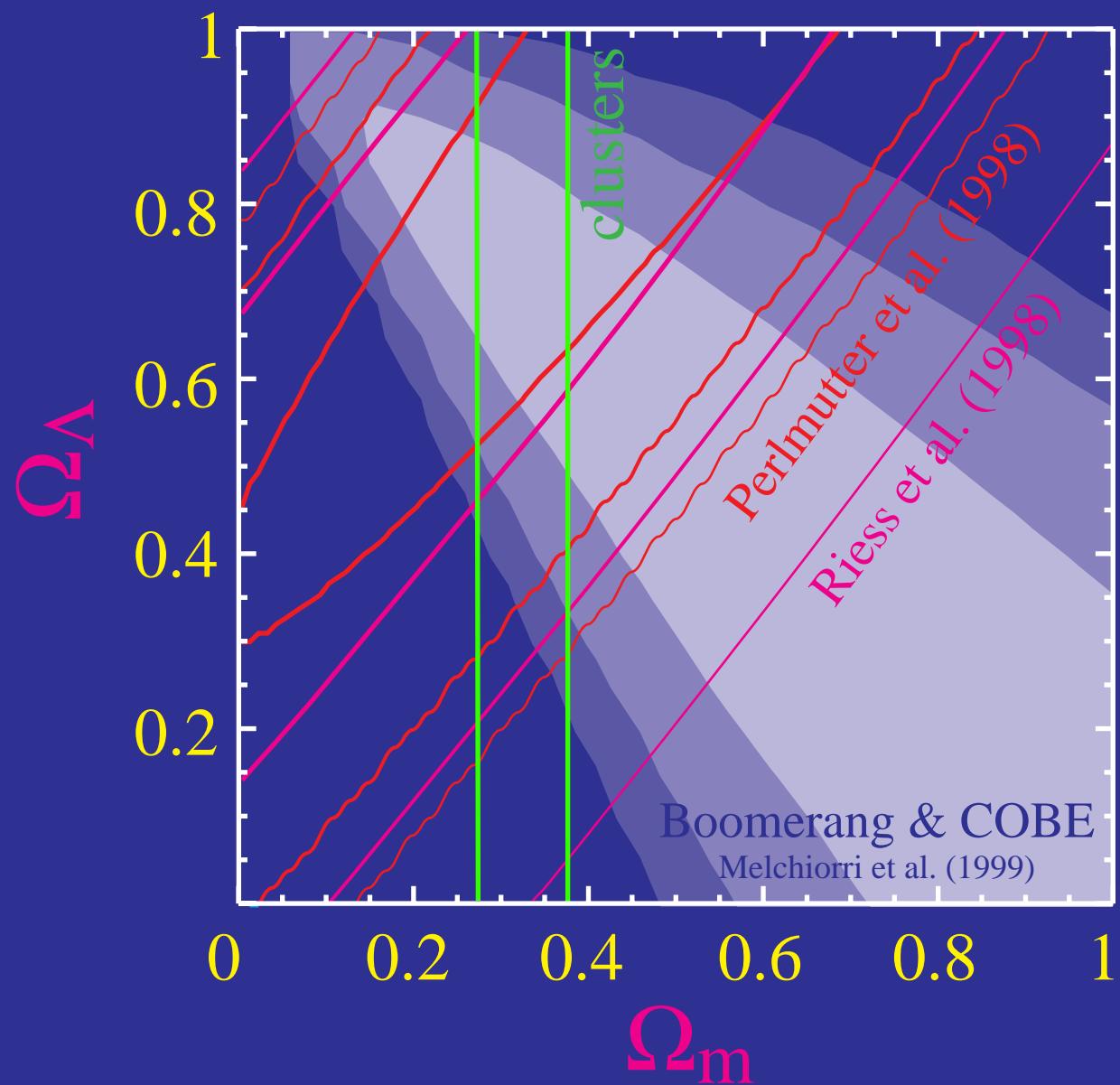
# Curvature and the Cosmological Constant



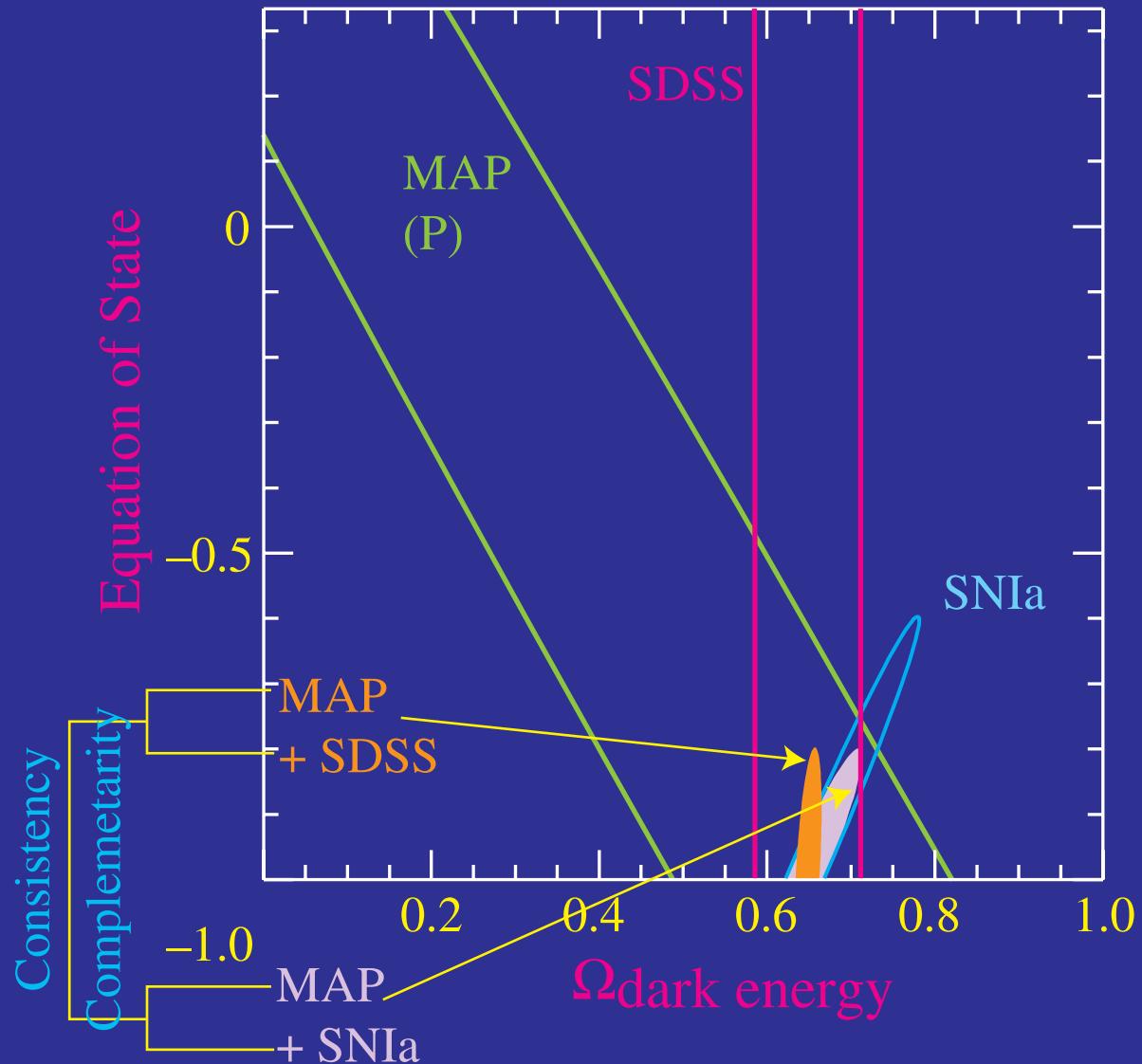
# Curvature & $\Lambda$ : Constraints



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# Dark Energy: Future Prospects



Hu, Eisenstein, Tegmark & White (1998)

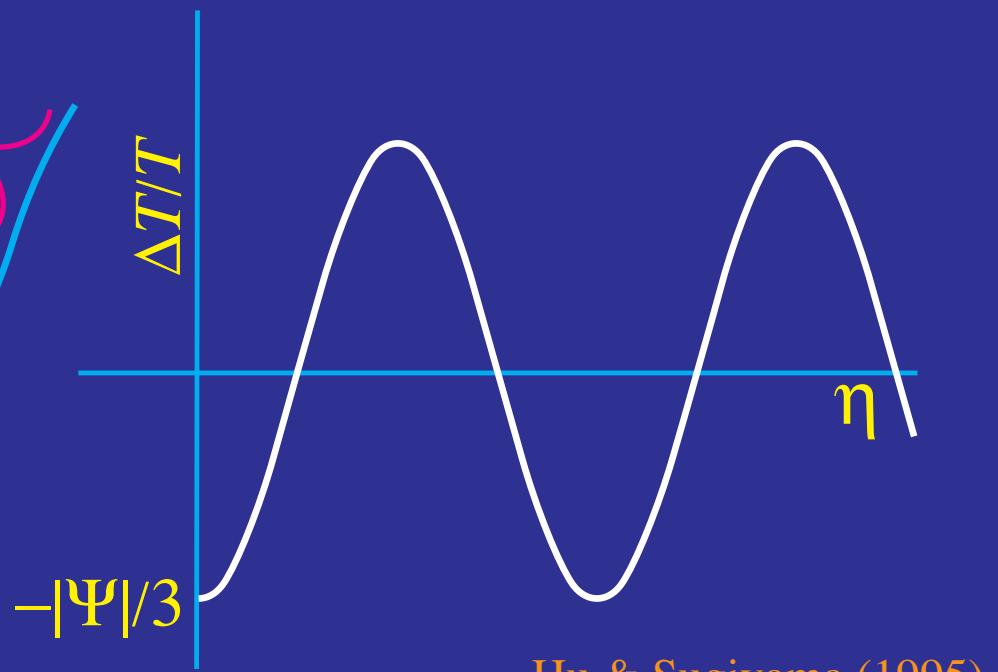
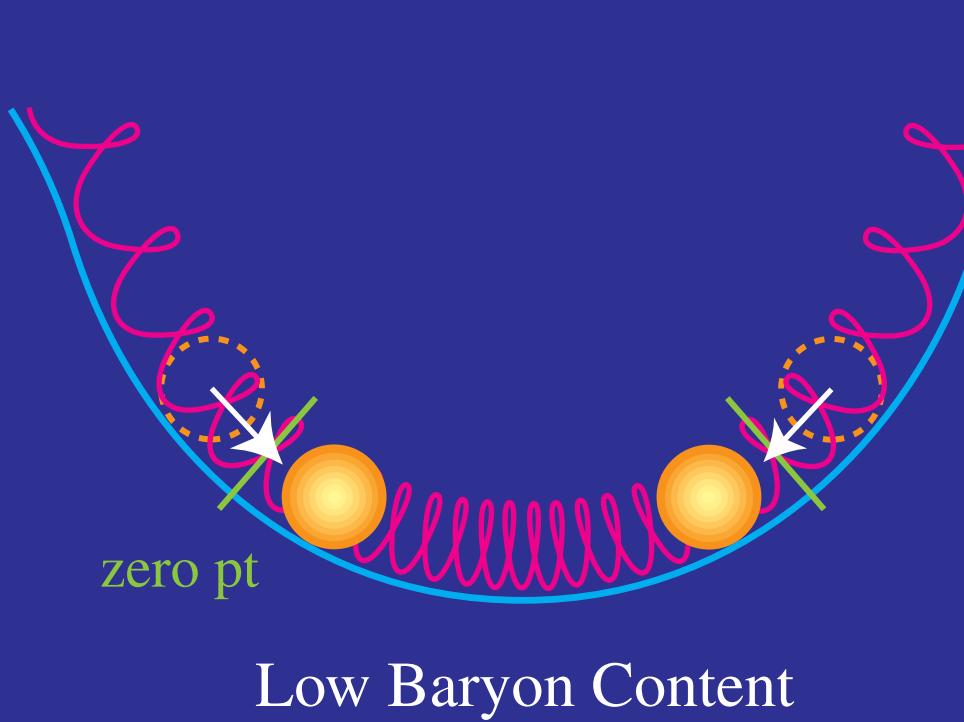
Current: Garnavich et al. (1999)

# Dark Baryons



# Baryon Drag

- Baryons provide **inertia**
- Relative momentum density  
$$R = (\rho_b + p_b)V_b / (\rho_\gamma + p_\gamma)V_\gamma \propto \Omega_b h^2$$
- Effective **mass**  $m_{\text{eff}} = (1 + R)$



Hu & Sugiyama (1995)

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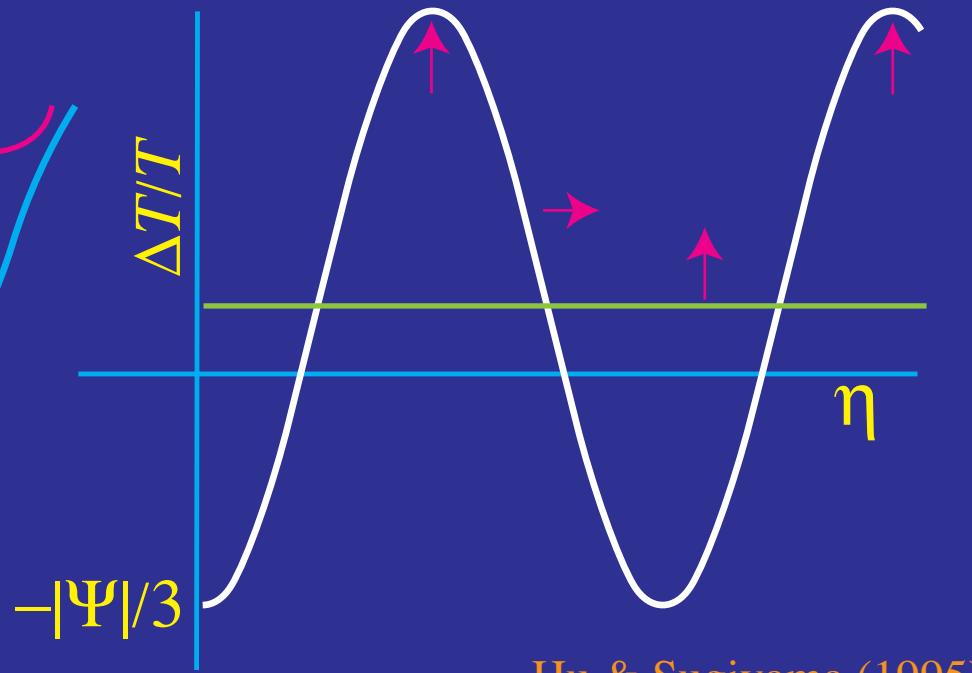
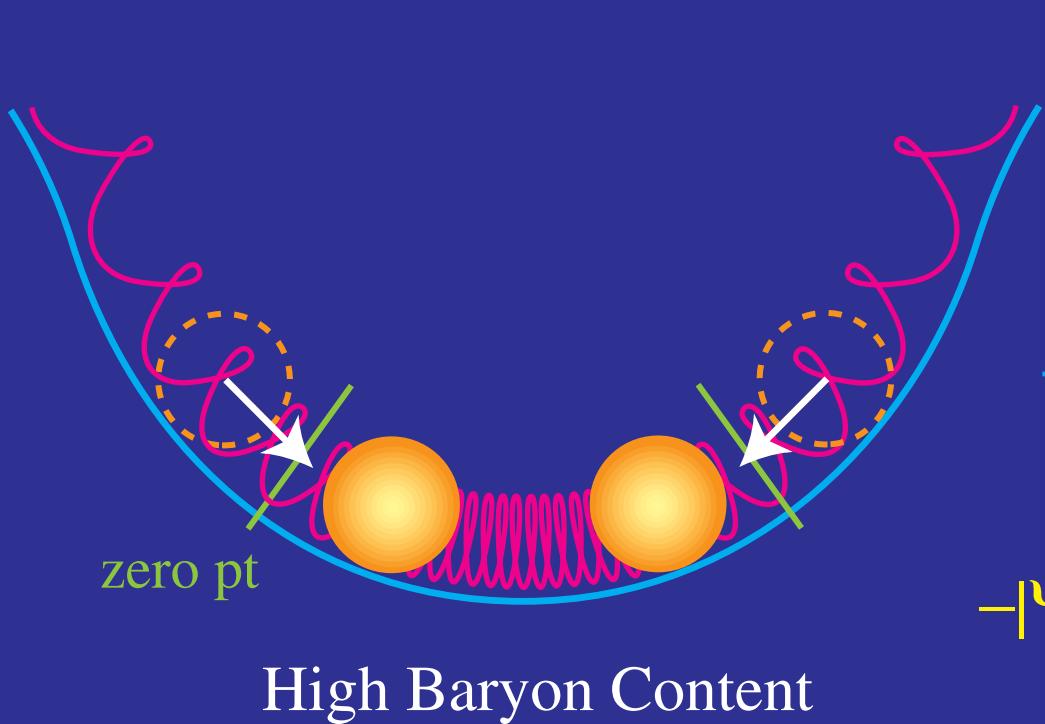
- Baryons drag photons into potential wells  $\rightarrow$  **zero point**  $\uparrow$

- Amplitude  $\uparrow$

- Frequency  $\downarrow$  ( $\omega \propto m_{\text{eff}}^{-1/2}$ )

- Constant  $R$ ,  $\Psi$ :  $(1+R)\ddot{\Theta} + (k^2/3)\Theta = -(1+R)(k^2/3)\Psi$

$$\Theta + \Psi = [\Theta(0) + (1+R)\Psi(0)] \cos [k\eta/\sqrt{3}(1+R)] - R\Psi$$



Hu & Sugiyama (1995)

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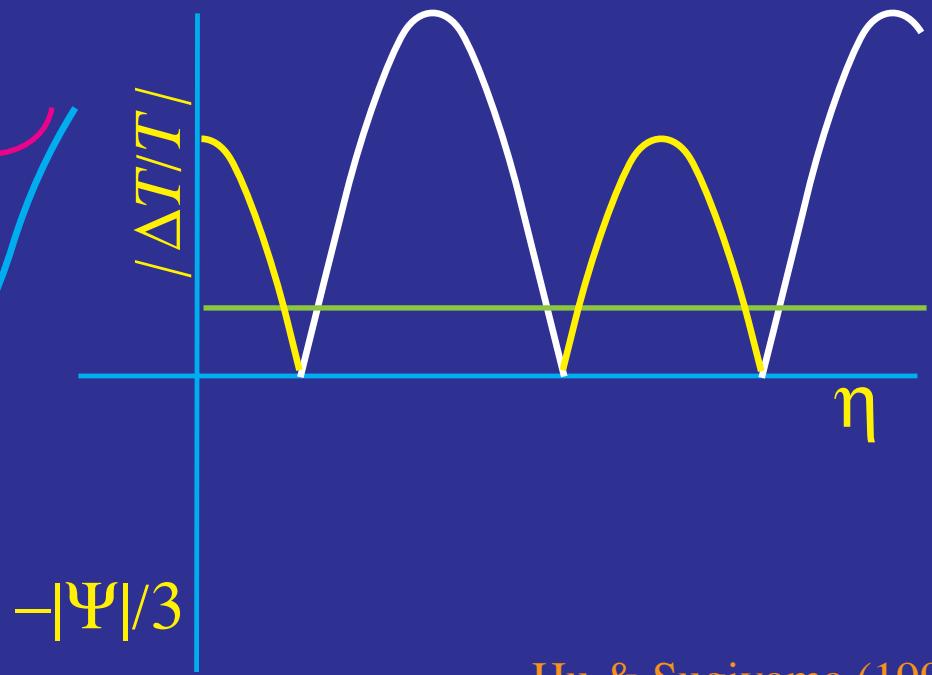
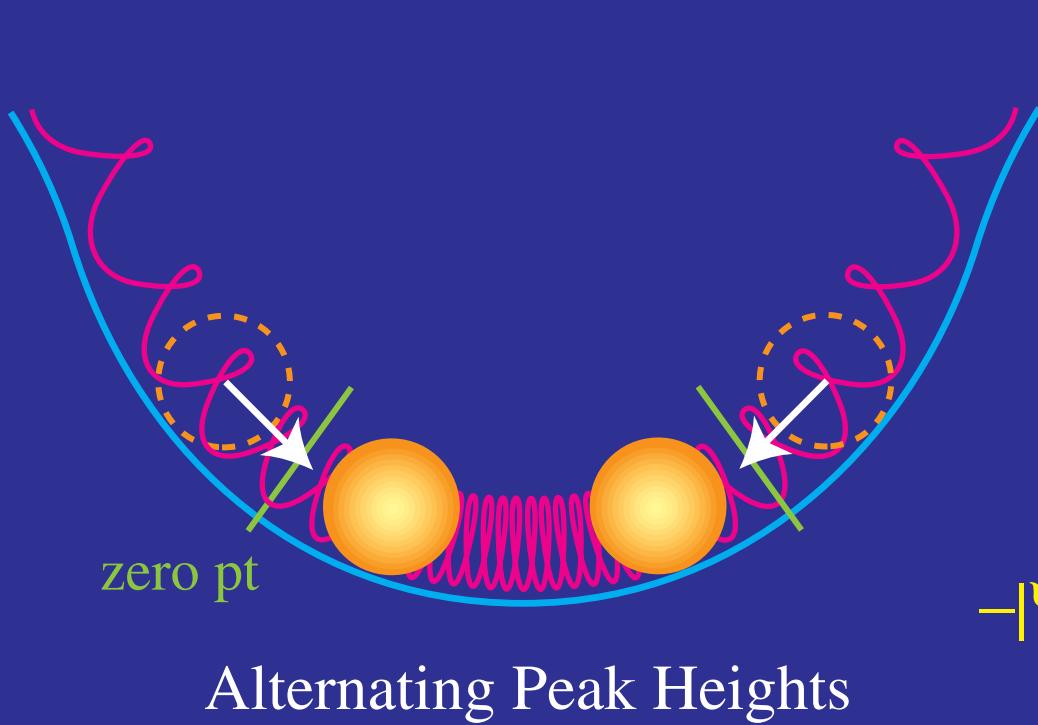
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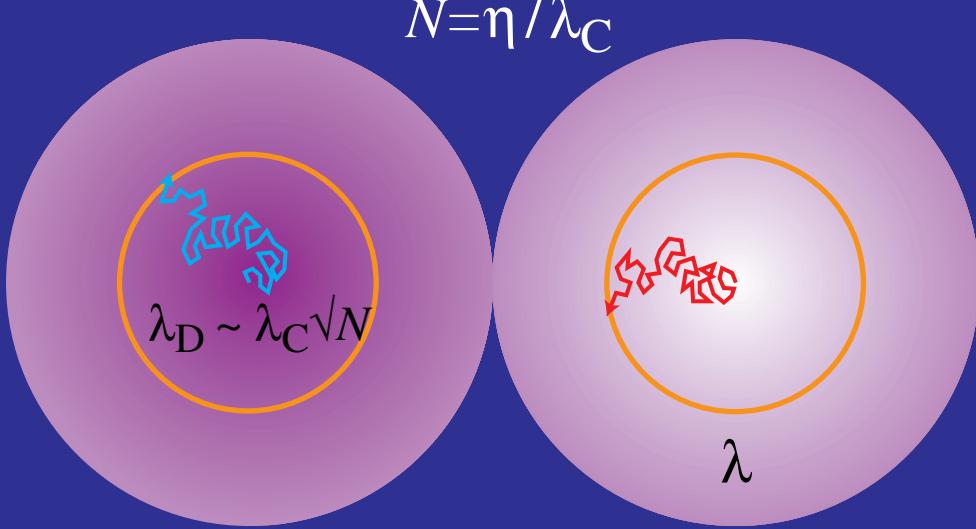
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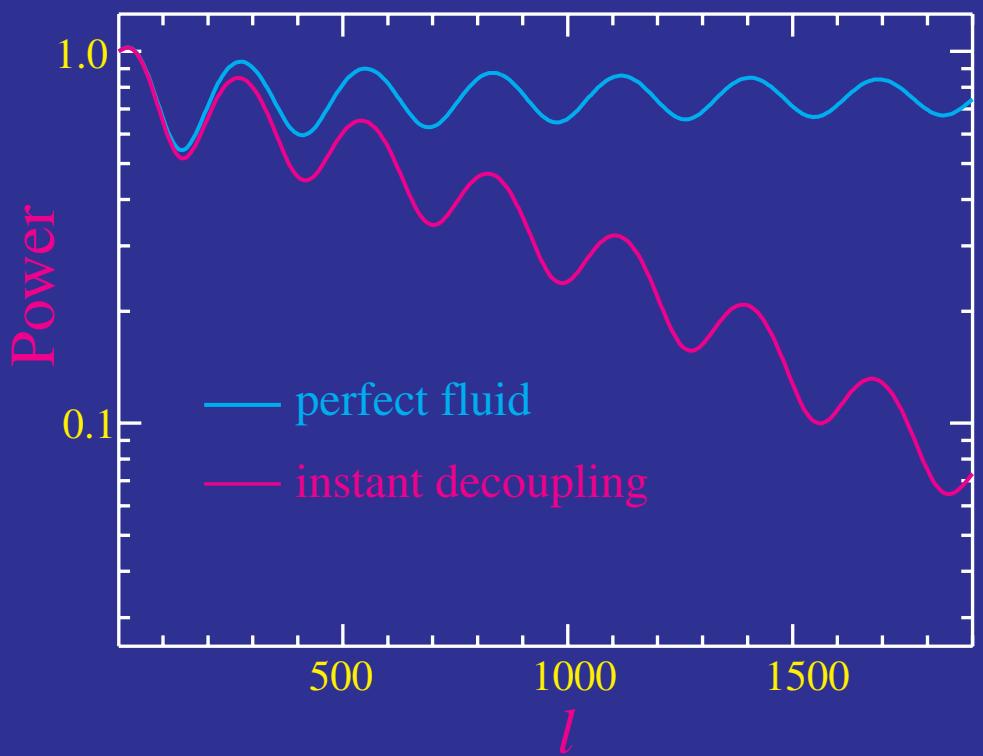
# Dissipation / Diffusion Damping

- Imperfections in the coupled fluid  $\rightarrow$  mean free path  $\lambda_C$  in the baryons
- Random walk over diffusion scale:  $\lambda_D \sim \lambda_C \sqrt{N} \sim \sqrt{\lambda_C \eta} \gg \lambda_C$   
viscous damping for  $R < 1$ ; heat conduction damping for  $R > 1$



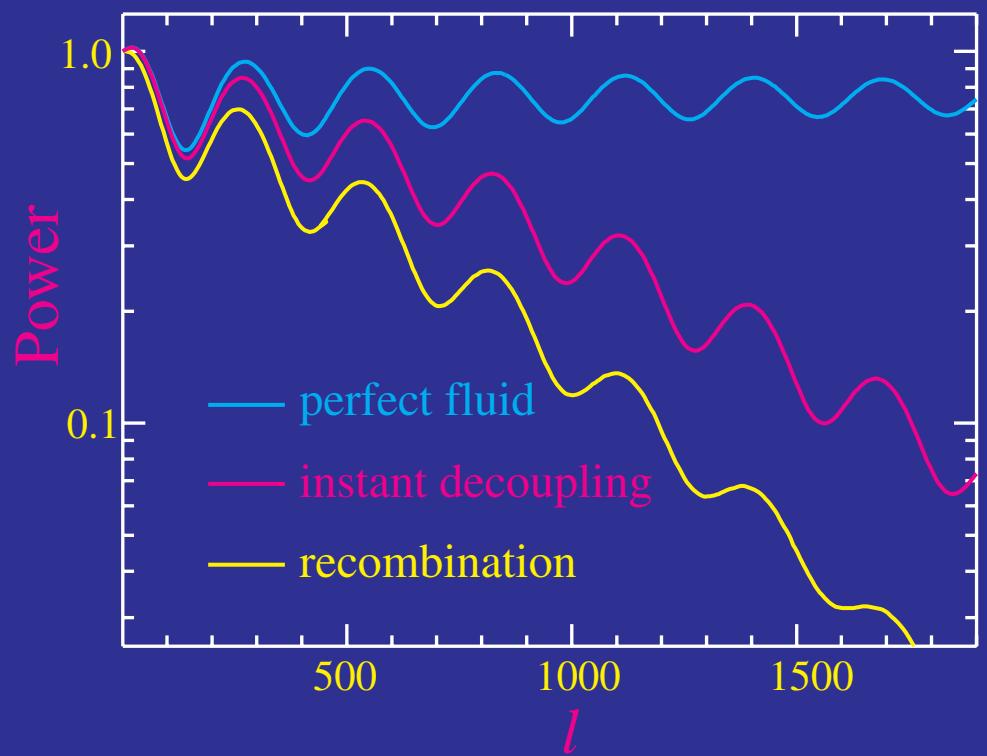
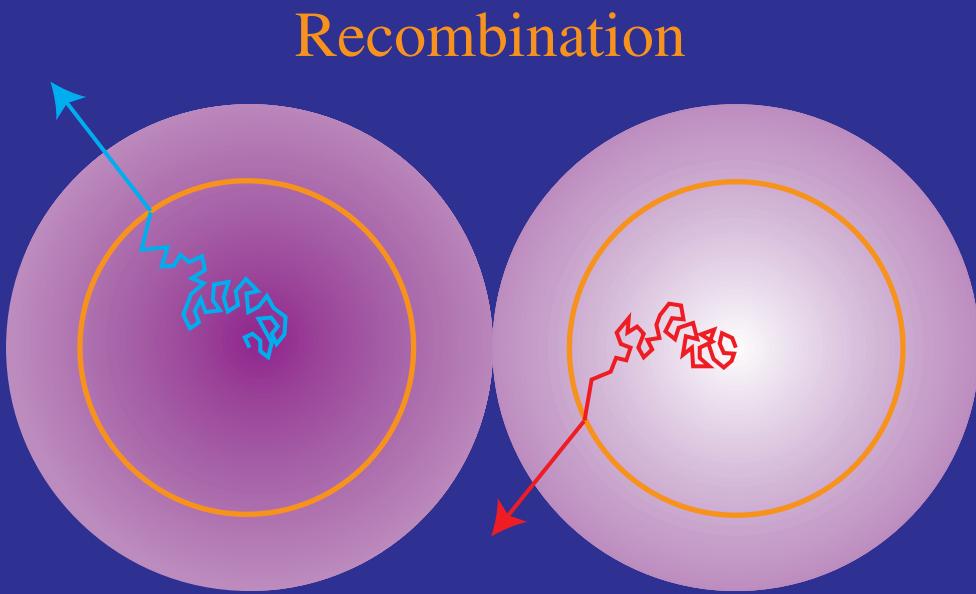
$$N = \eta / \lambda_C$$

Silk (1968)

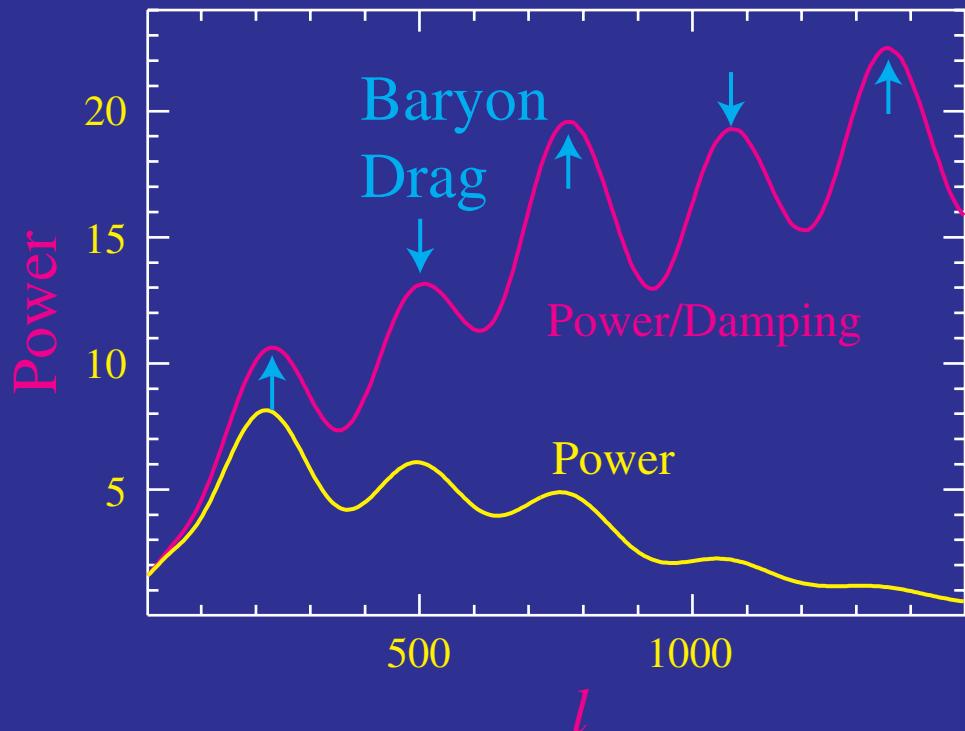


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  - Rapid increase at recombination as mfp  $\uparrow$
- 
- Peak/Damping angular scale: calibrate  $\Omega_b h^2$  or test recombination
  - Robust physical scale for angular diameter distance test ( $\Omega_K$ ,  $\Omega_\Lambda$ )

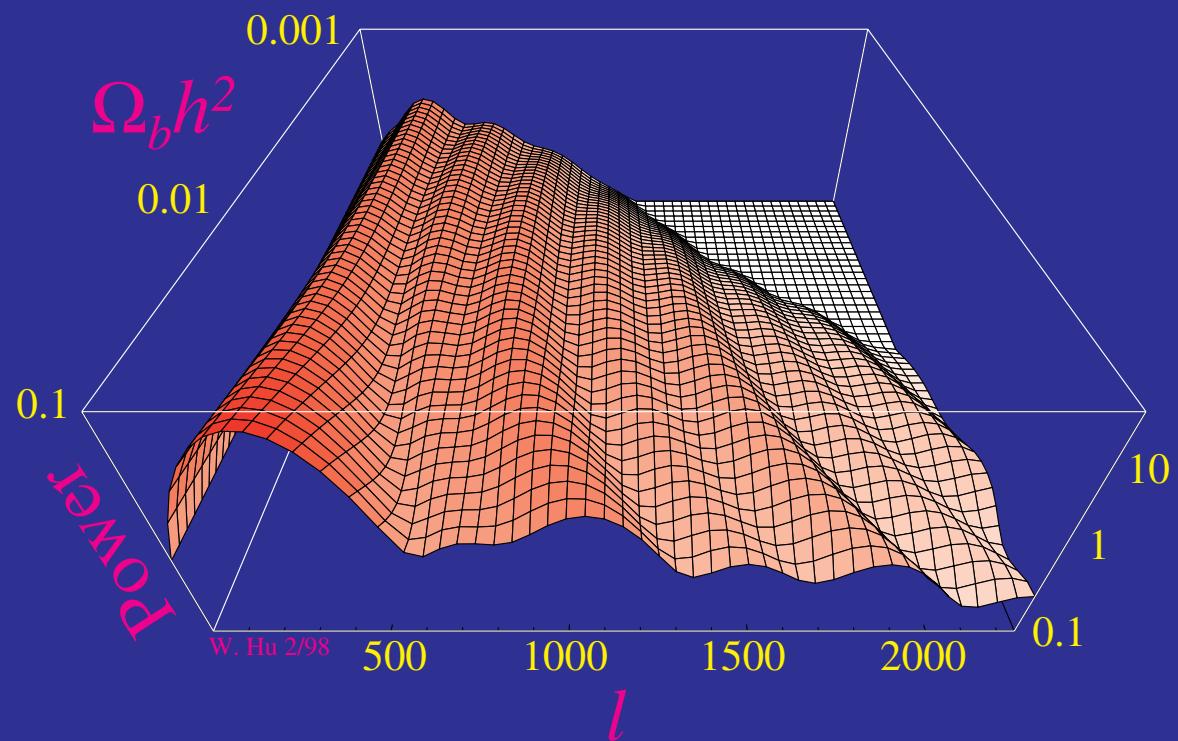


# Baryons in the CMB



- Additional Effects
  - Time-varying potential
  - Dissipation/Fluid imperfections

- High odd peaks

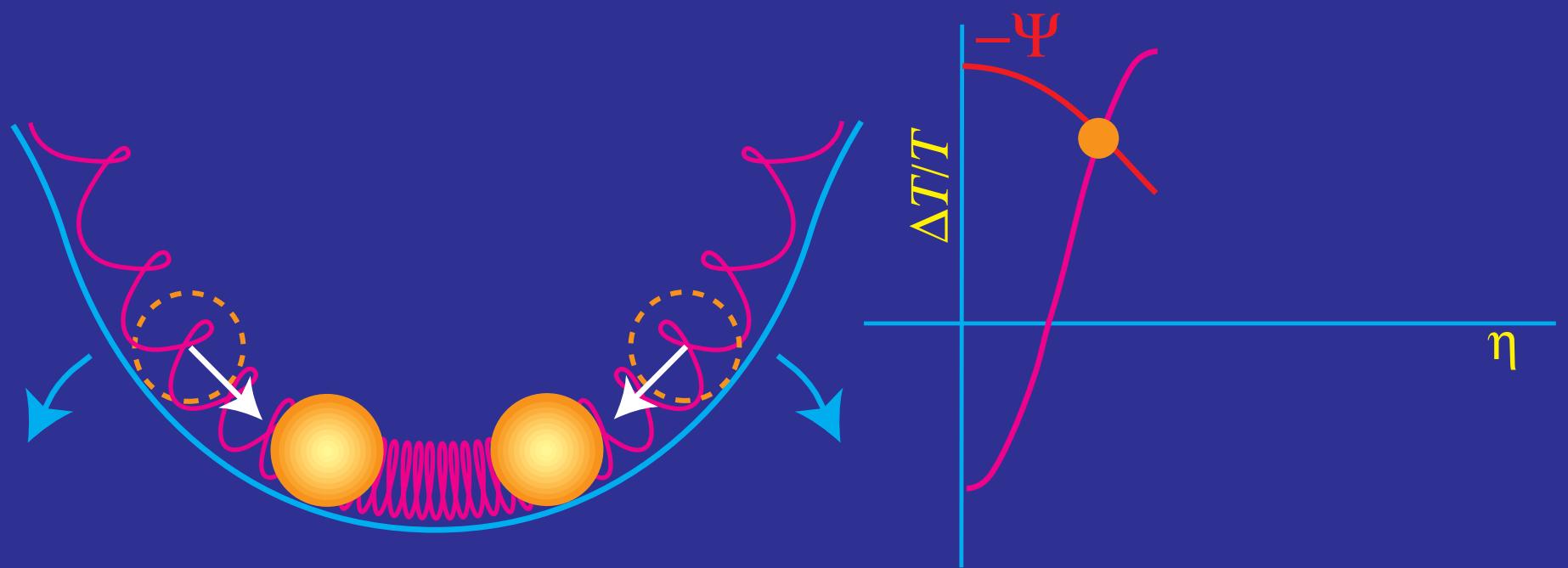


# Matter–Radiation Ratio

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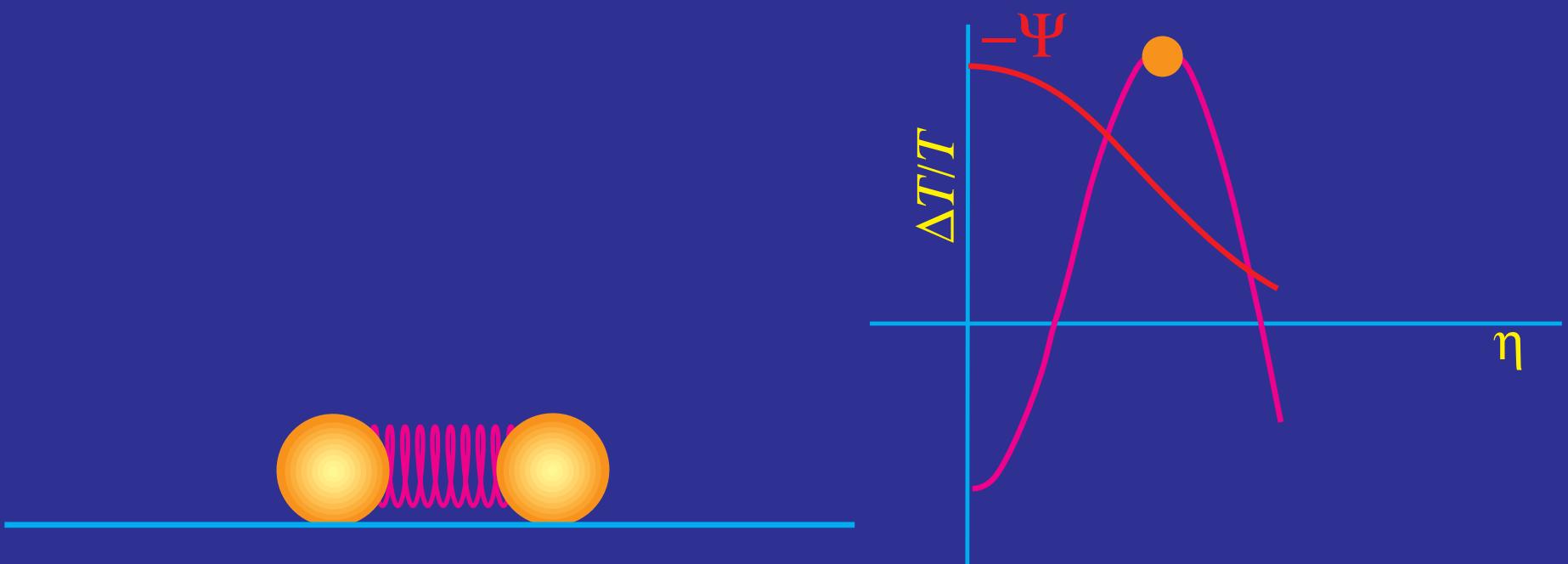
# Driving Effects and Matter/Radiation

- Potential perturbation:  $k^2\Psi = -4\pi Ga^2\delta\rho$  generated by radiation
- Radiation  $\rightarrow$  Potential: inside sound horizon  $\delta\rho/\rho$  pressure supported  $\delta\rho$  hence  $\Psi$  decays with expansion



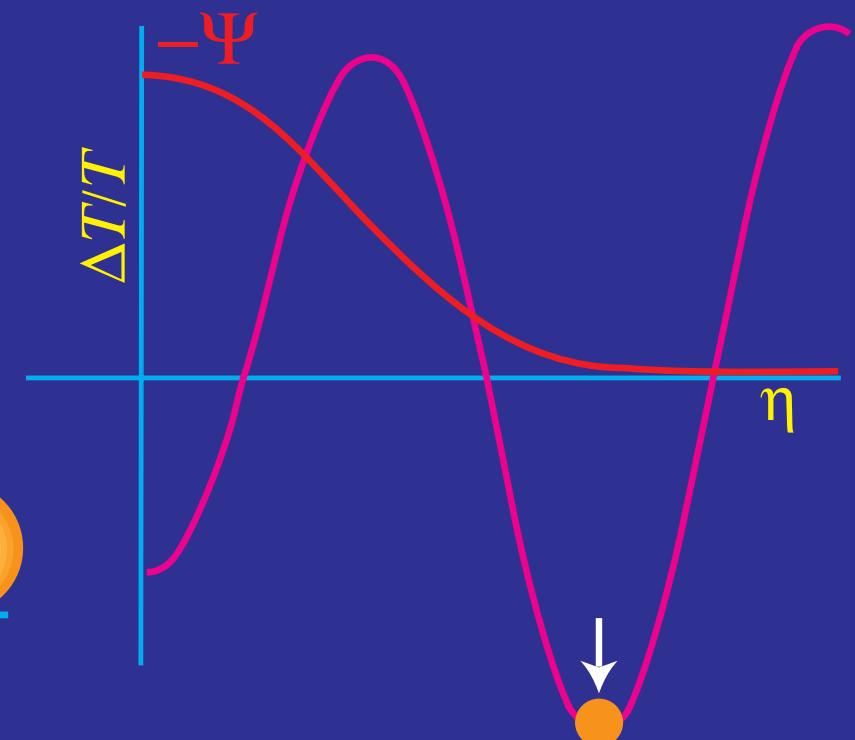
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- Potential  $\rightarrow$  Radiation:  $\Psi$ -decay timed to drive oscillation  
 $-2\Psi + (1/3)\Psi = -(5/3)\Psi \rightarrow 5x$  boost
- Feedback stops at matter domination

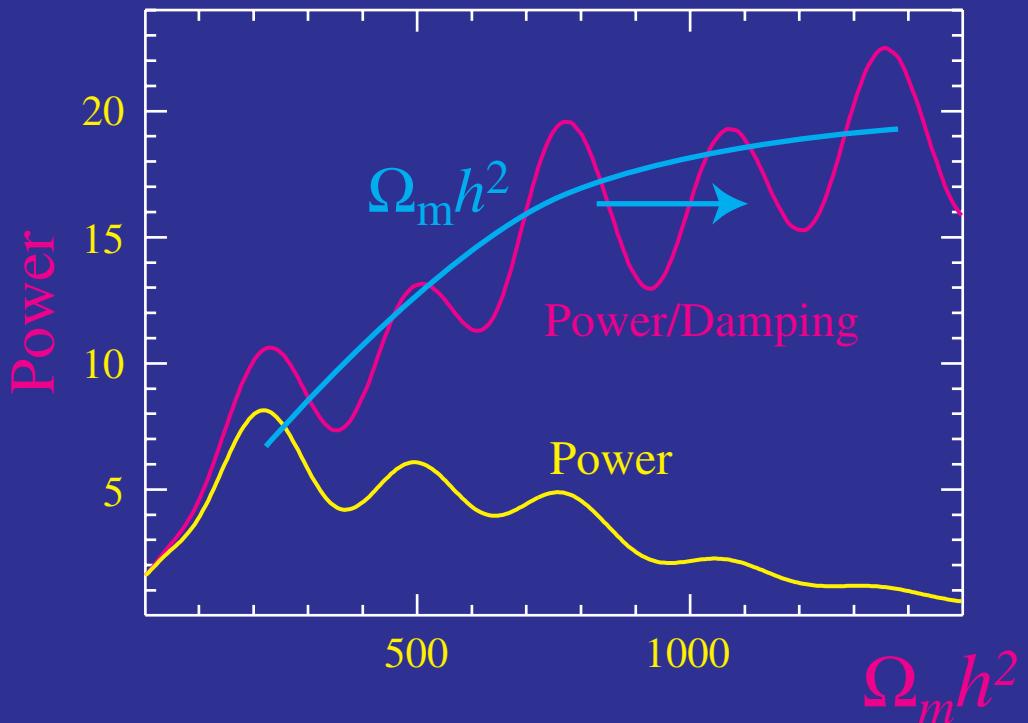


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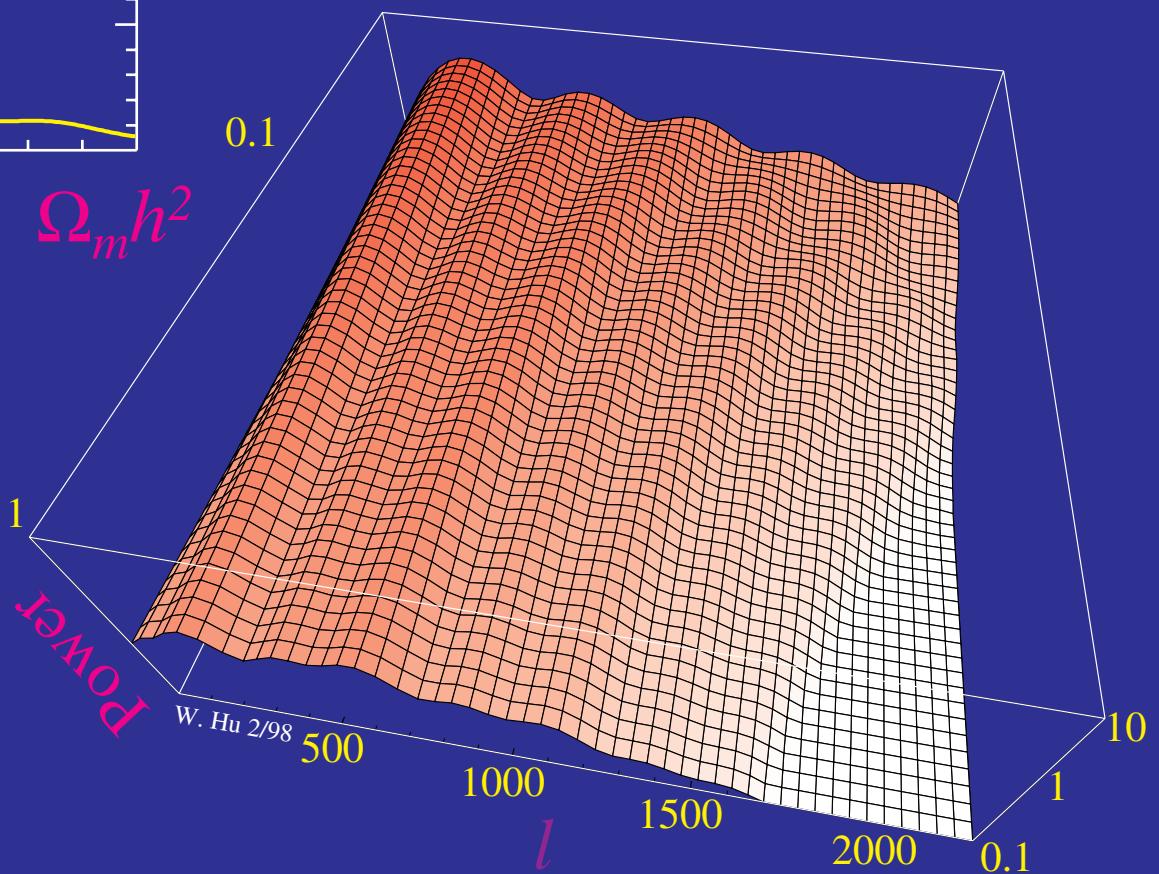
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# Matter Density in the CMB



- Amplitude ramp across matter–radiation equality
- Radiation density fixed by CMB temperature & thermal history



- Measure  $\Omega_m h^2$  from peak heights

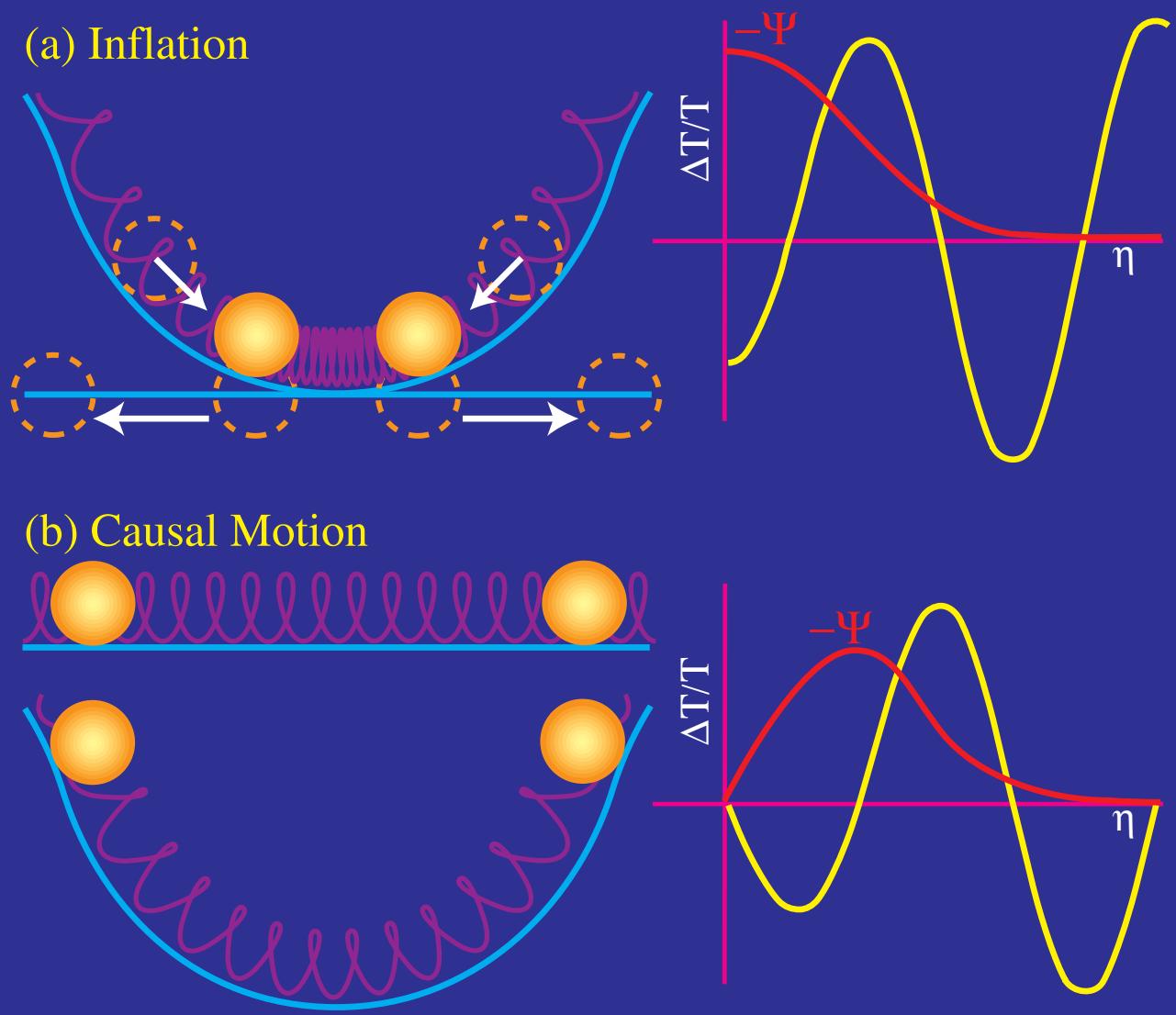
# 1 . 2 . 3

## Inflation & The Origin of Perturbations

# Inflation as Source of Perturbations

- Superluminal expansion (inflation) required to generate superhorizon potential (density) perturbations
- Potential perturbations drive oscillations
- (Nearly) unique prediction for phase
- Ratio of peak locations  
inflation: 1:2:3...

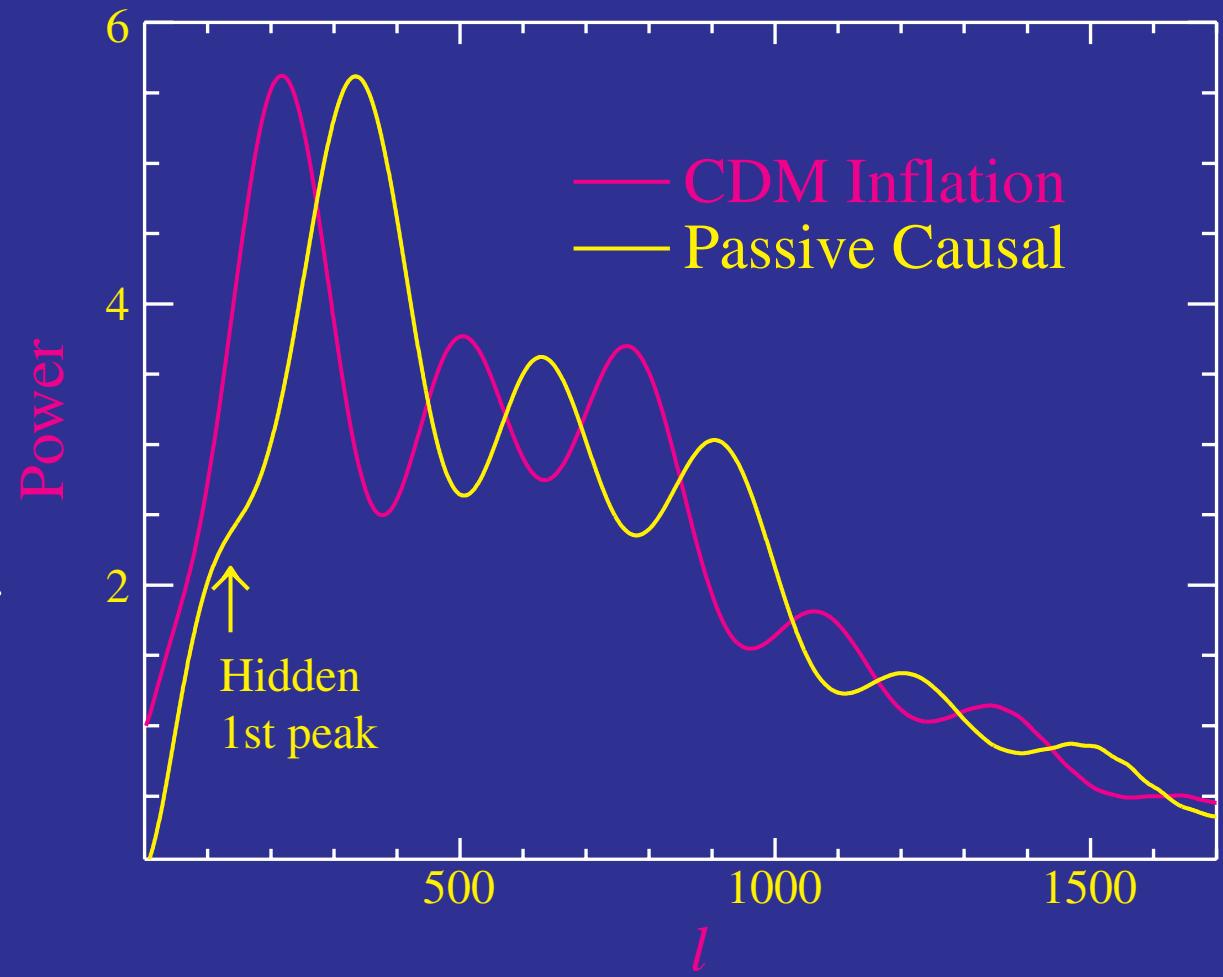
passive causal  
models: 1:3:5...  
active causal  
models: no peaks



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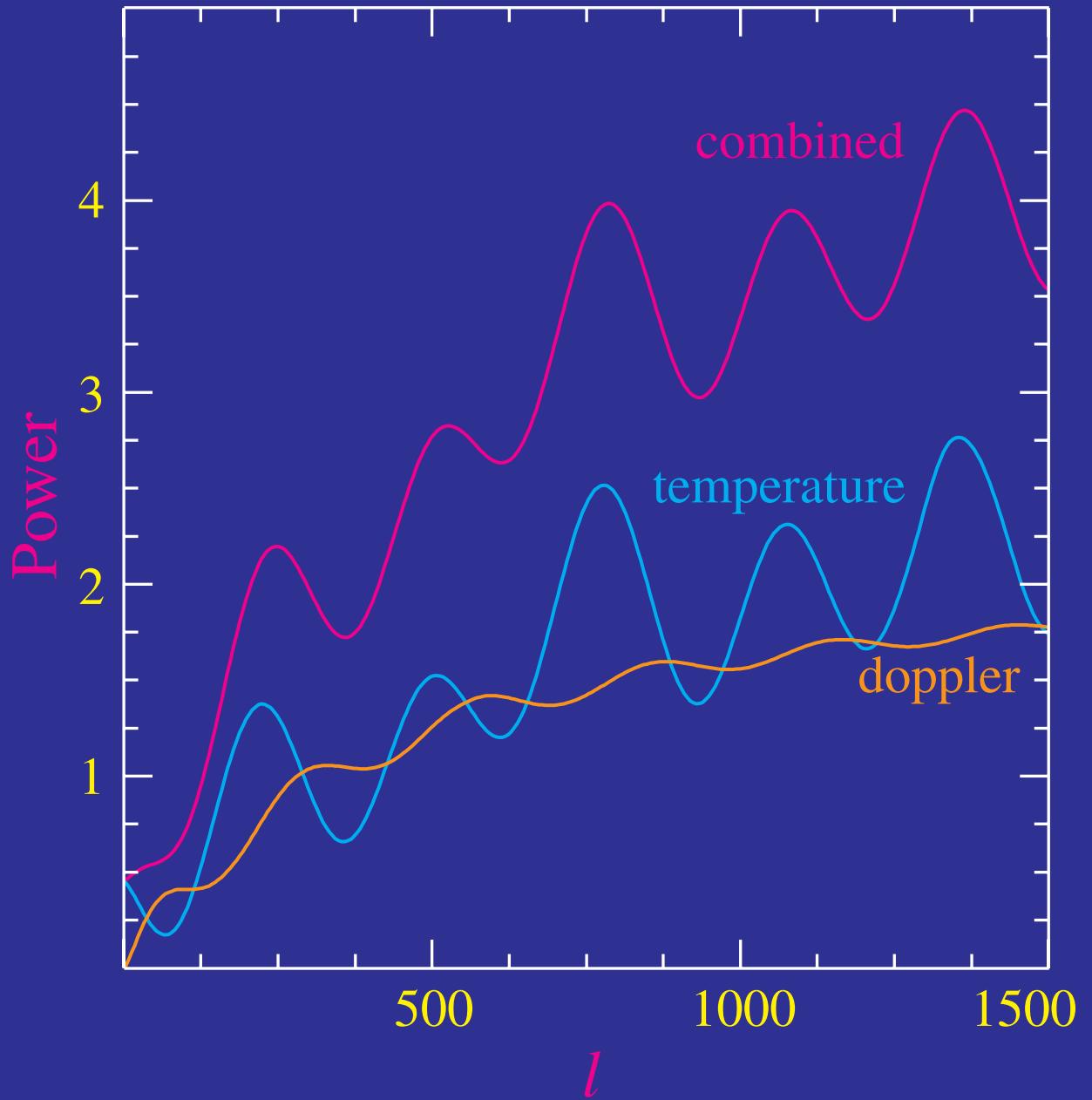
1:2:3 strongly suggests inflation but not necessarily the adiabatic or isocurvature nature of initial conditions



(Hu 1998; Hu & Peebles 1999)

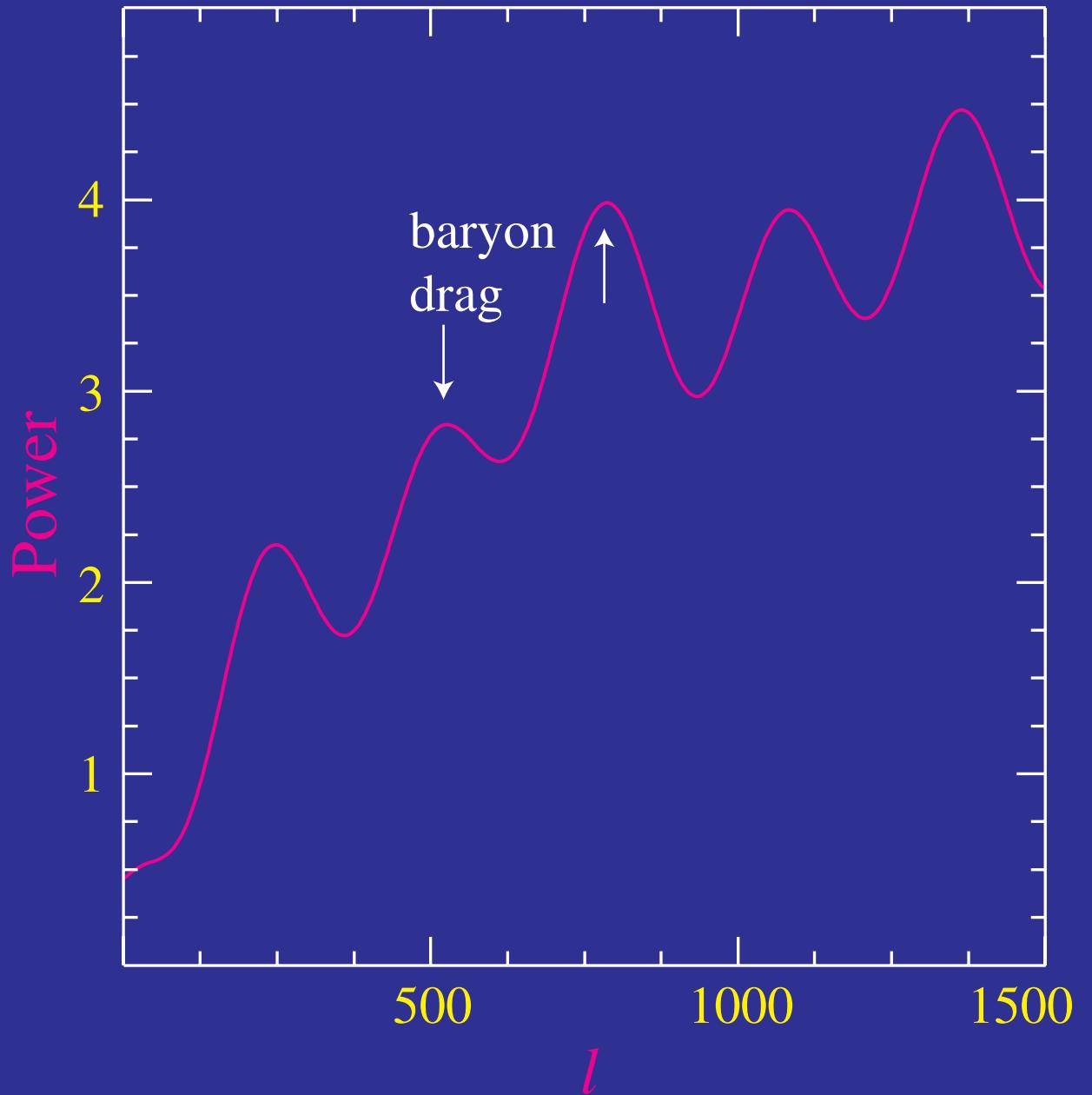
# Summary of Acoustic Phenomenology

- Fluid + Gravity  
→ harmonic series:  
inflationary origin



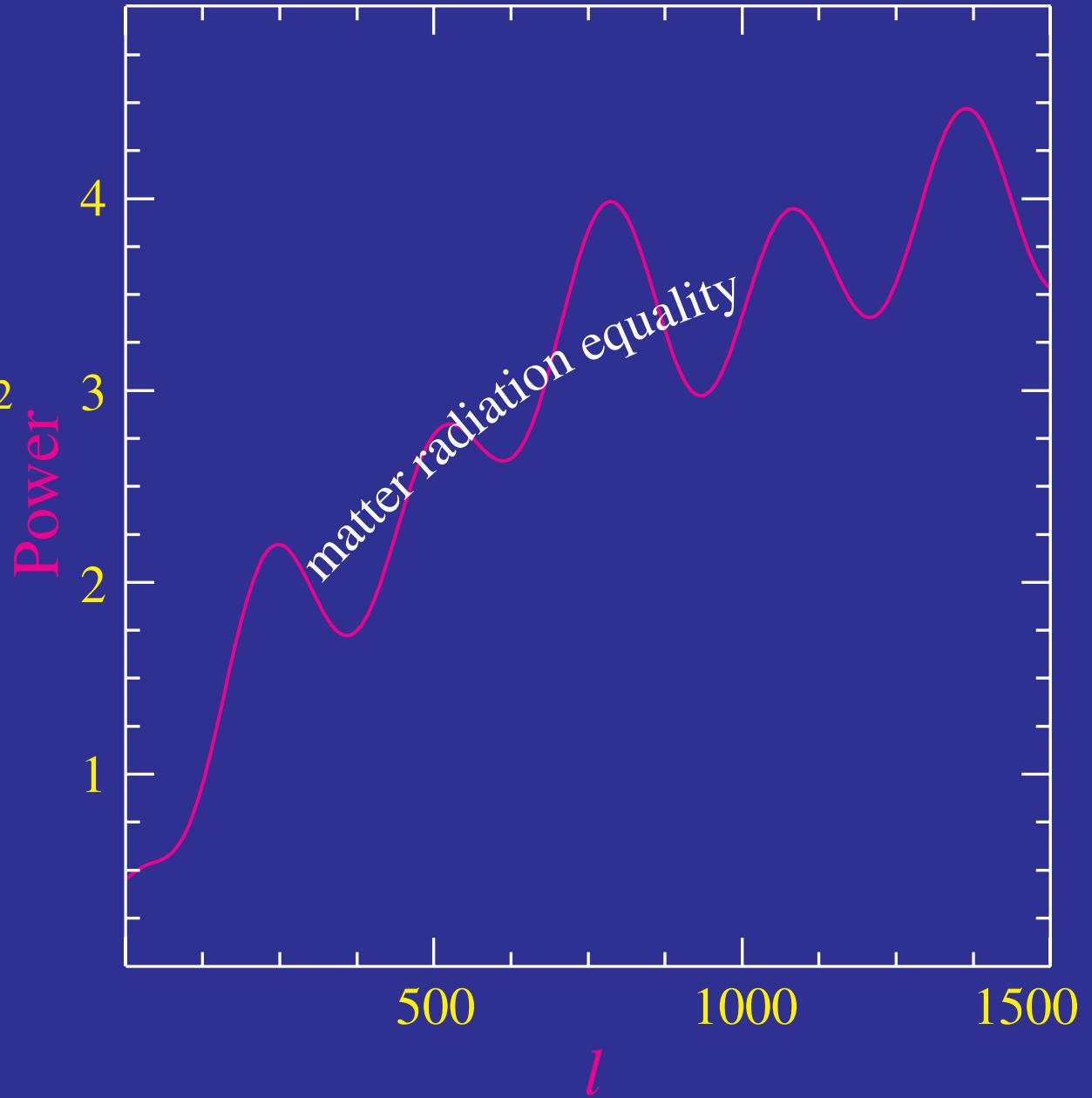
# Summary of Acoustic Phenomenology

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inflationary origin
  - alternating peaks:  
photon/baryon  $\Omega_b h^2$



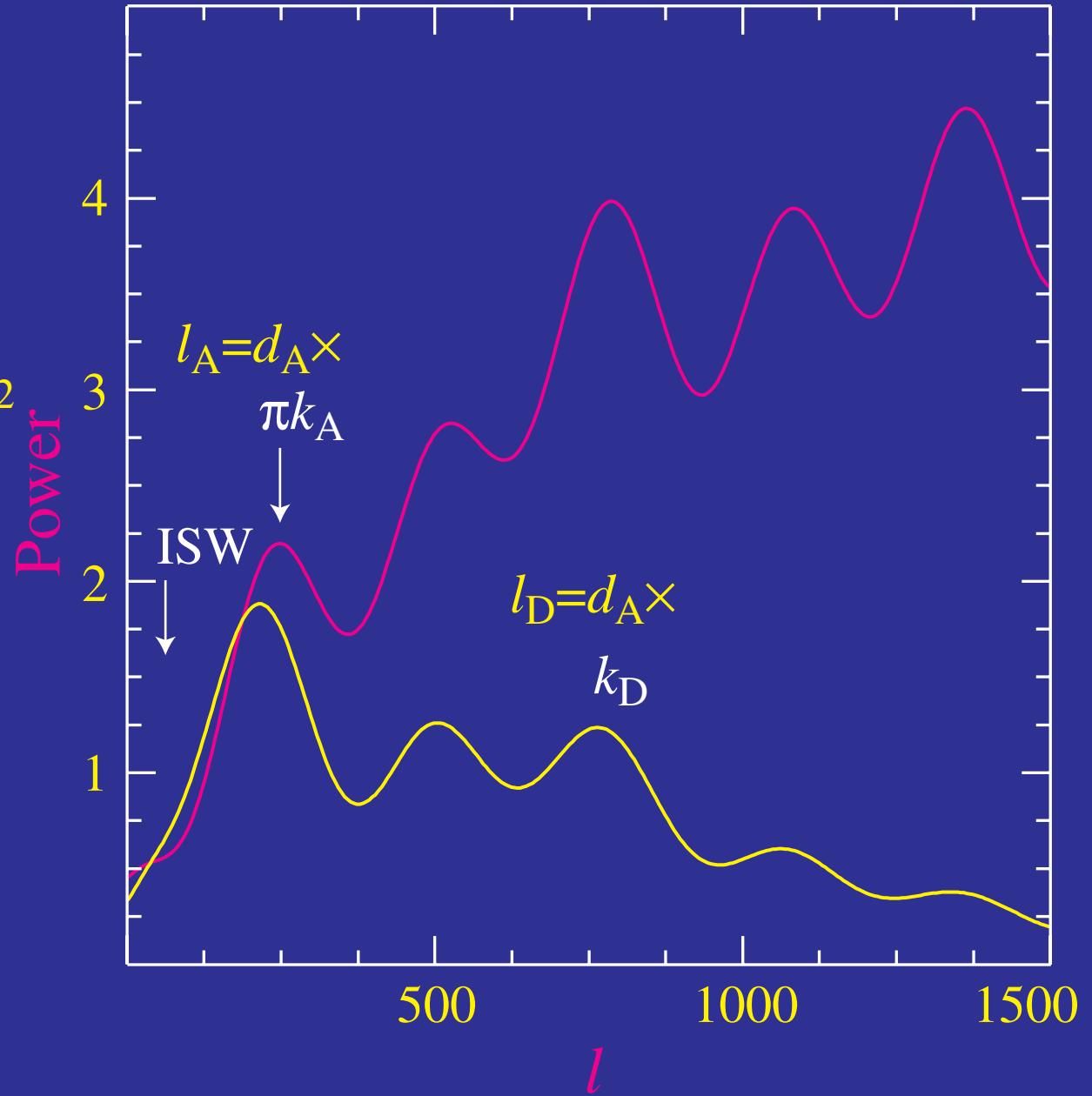
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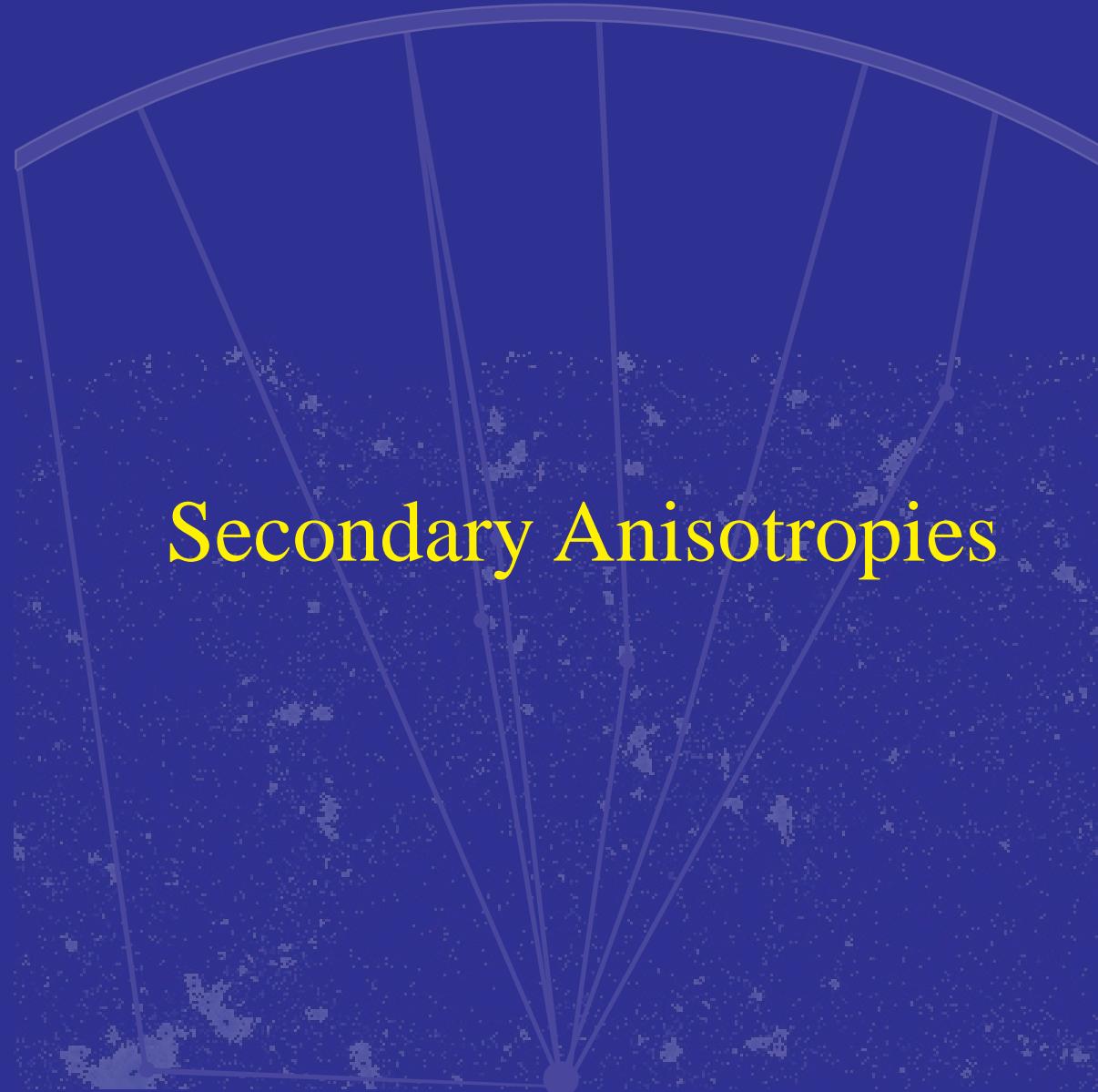


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photon/baryon  $\Omega_b h^2$
  - driven oscillations:  
matter/radiation  $\Omega_m h^2$
- Ruler Calibration
  - sound horizon
  - damping scale
- Geometry
  - angular diameter distance  $f(\Omega_\Lambda, \Omega_K)$
  - + flatness or no  $\Omega_\Lambda$ ,
  - $\Omega_\Lambda$  or  $\Omega_K$

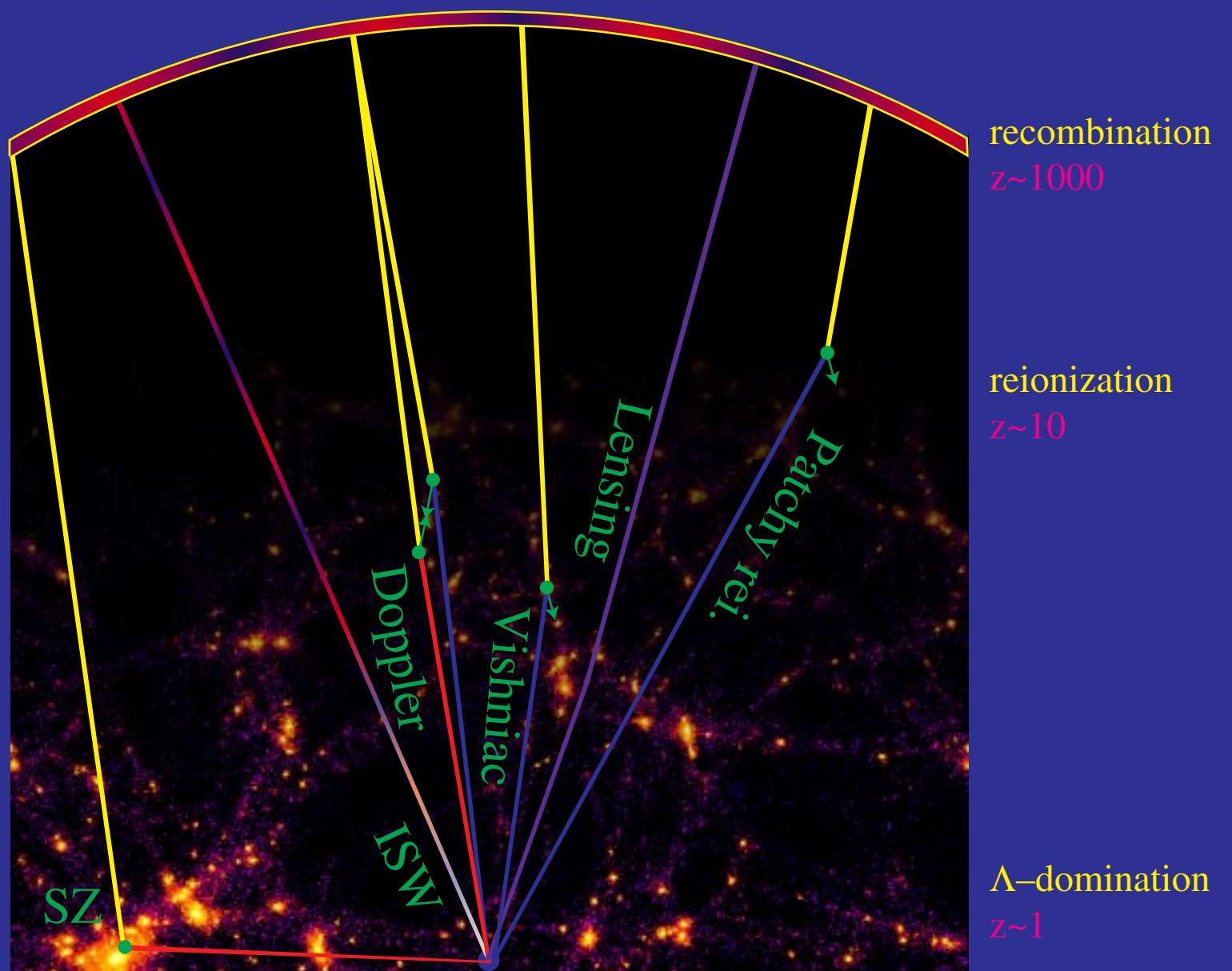


# Secondary Anisotropies



# Physics of Secondary Anisotropies

Primary Anisotropies



# Secondary Anisotropies: Power Spectra

- Gravitational Effects

- ISW Effect

- (redshift from decaying potentials)

- Weak Lensing

- (smooths peaks and generates power  $<1'$ )

- Scattering Effects

- Doppler Effect

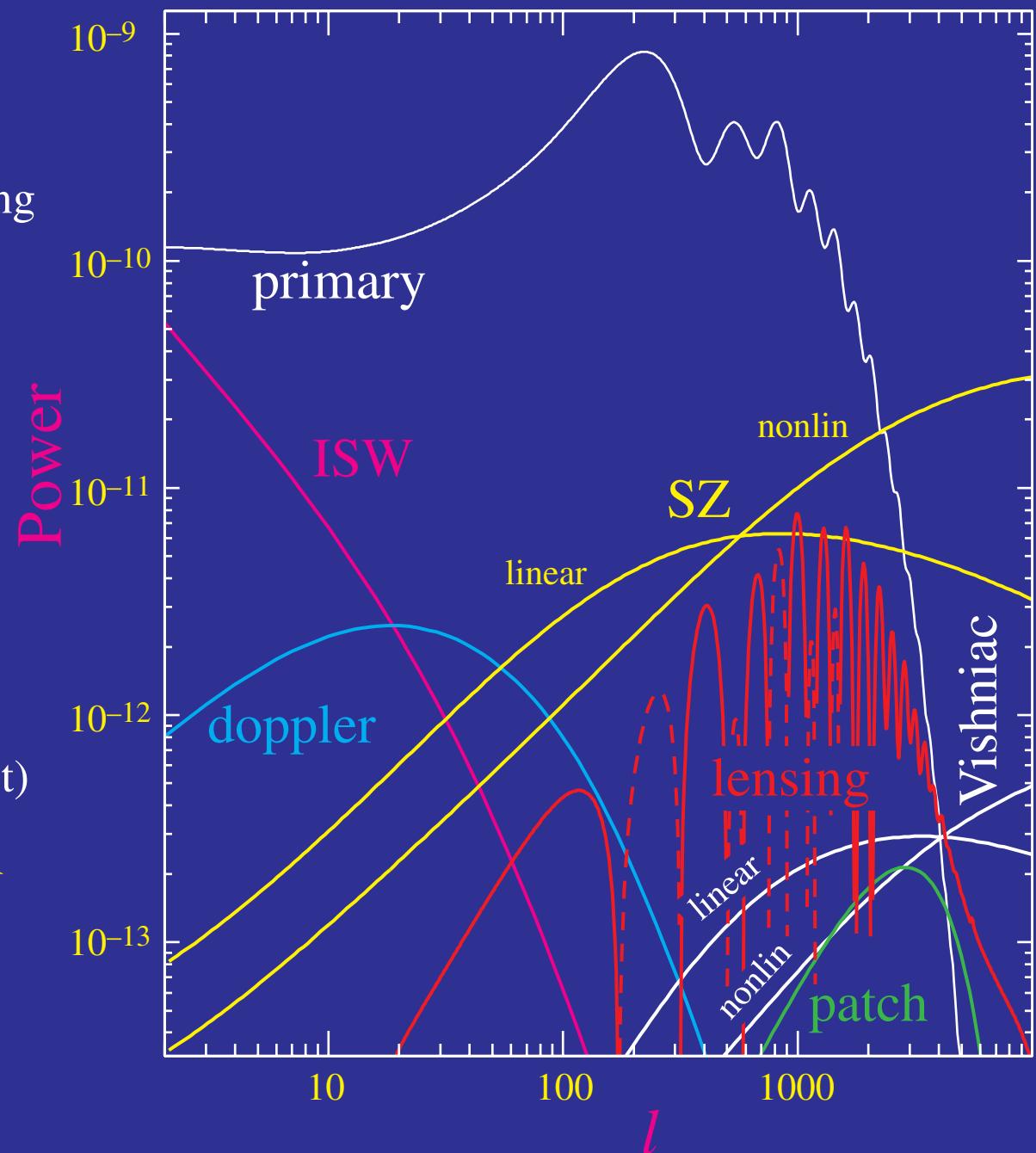
- Vishniac Effect

- (LSS kinetic SZ effect)

- Patchy Reionization

- SZ effect

- (LSS thermal)



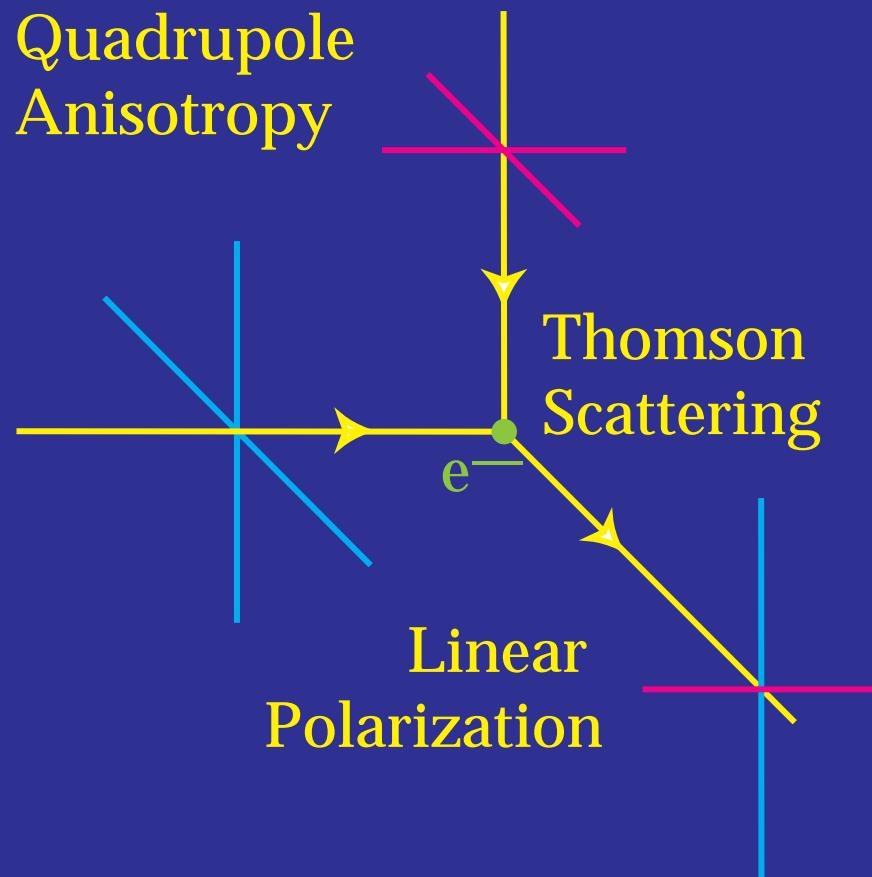
# Recent Work on Isolating Secondary Anisotropies

- Subarcminute Power Spectrum  
Vishniac Effect; Kinetic SZ Effect;  
Patchy Reionization [Hu \(1999\)](#)  
[Bruscoli et al. \(1999\)](#)  
**SZ in Clusters**  
[Komatsu & Kitayama \(1999\)](#)  
**SZ in Radio Galaxies**  
[Yamada, Sugiyama, Silk \(1999\)](#)
- Polarization  
**Weak Lensing**  
[Zaldarriaga & Seljak \(1999\)](#)  
[Guzik, Seljak & Zaldarriaga \(1999\)](#)  
**Secondary Scattering**  
[Hu \(1999\); Weller \(1999\)](#)
- Frequency spectrum  
**SZ Effect**  
[Bouchet & Gispert \(1999\); Tegmark et al. \(1999\)](#)  
[Cooray, Hu & Tegmark \(2000\)](#)
- Temperature non-Gaussianity  
**Weak Lensing & Secondaries**  
3pt function (bispectrum)  
[Goldberg & Spergel \(1999\),](#)  
[Seljak & Zaldarriaga \(1999\),](#)  
[Cooray & Hu \(1999\)](#)  
**Weak Lensing: 4pt function**  
(trispectrum) [Zaldarriaga \(1999\)](#)  
spot ellipticity & correlation  
[Van Waerbeke, Bernardeau & Benabed \(1999\)](#)
- **SZ Effect:** hydro-simulations  
[da Silva et al. \(1999\); Refrigier et al. \(1999\),](#)  
[Seljak, Burwell, Pen \(2000\);](#)  
**Press-Schechter** [Aghanim & Forni \(1999\);](#)
- **Polarization non-Gaussianity**  
[Hu \(2000\)](#)

# Polarization

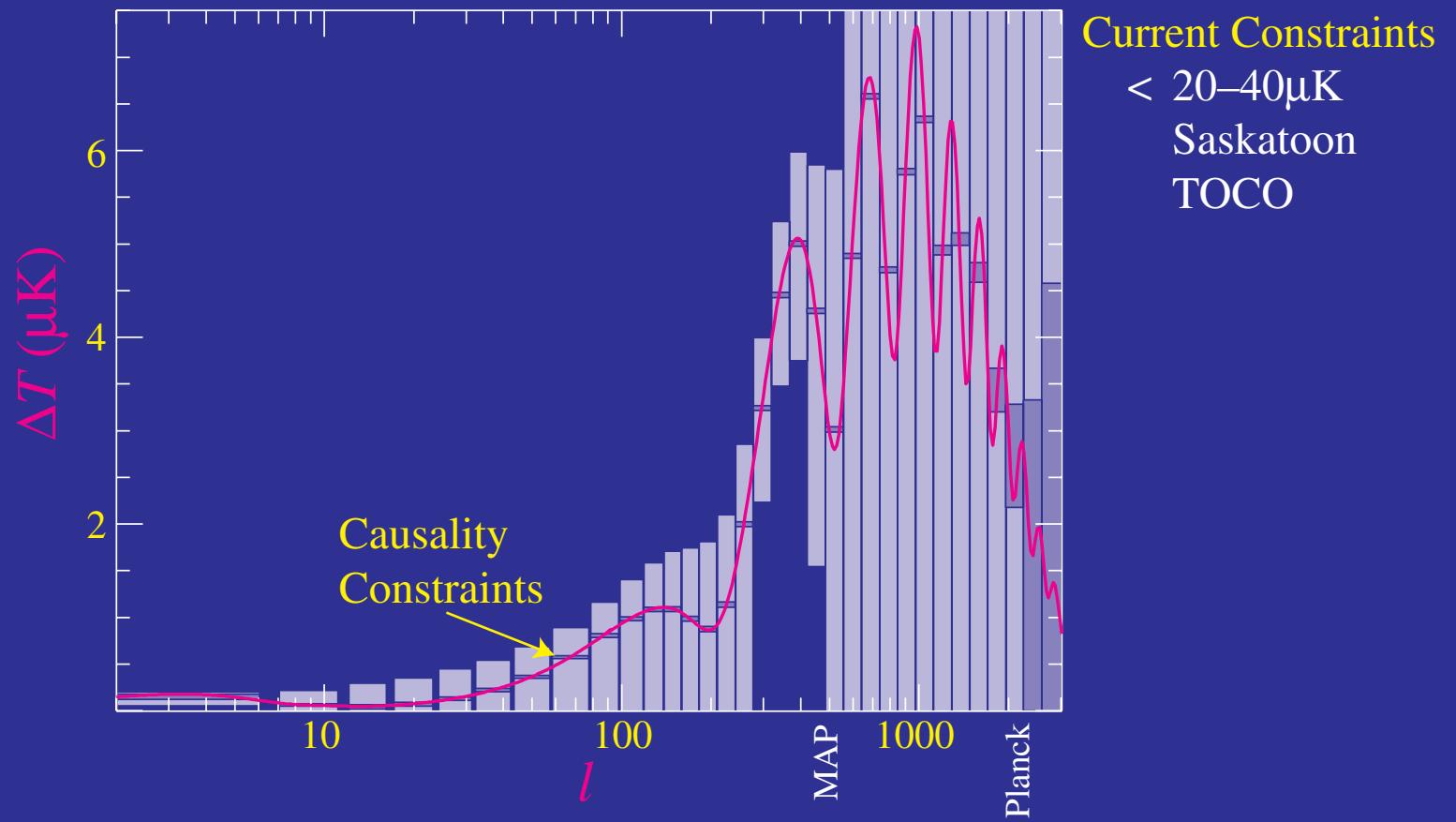
# Polarization Diagnostics

- CMB polarization generated by scattering of quadrupole anisotropies



# Polarization Diagnostics

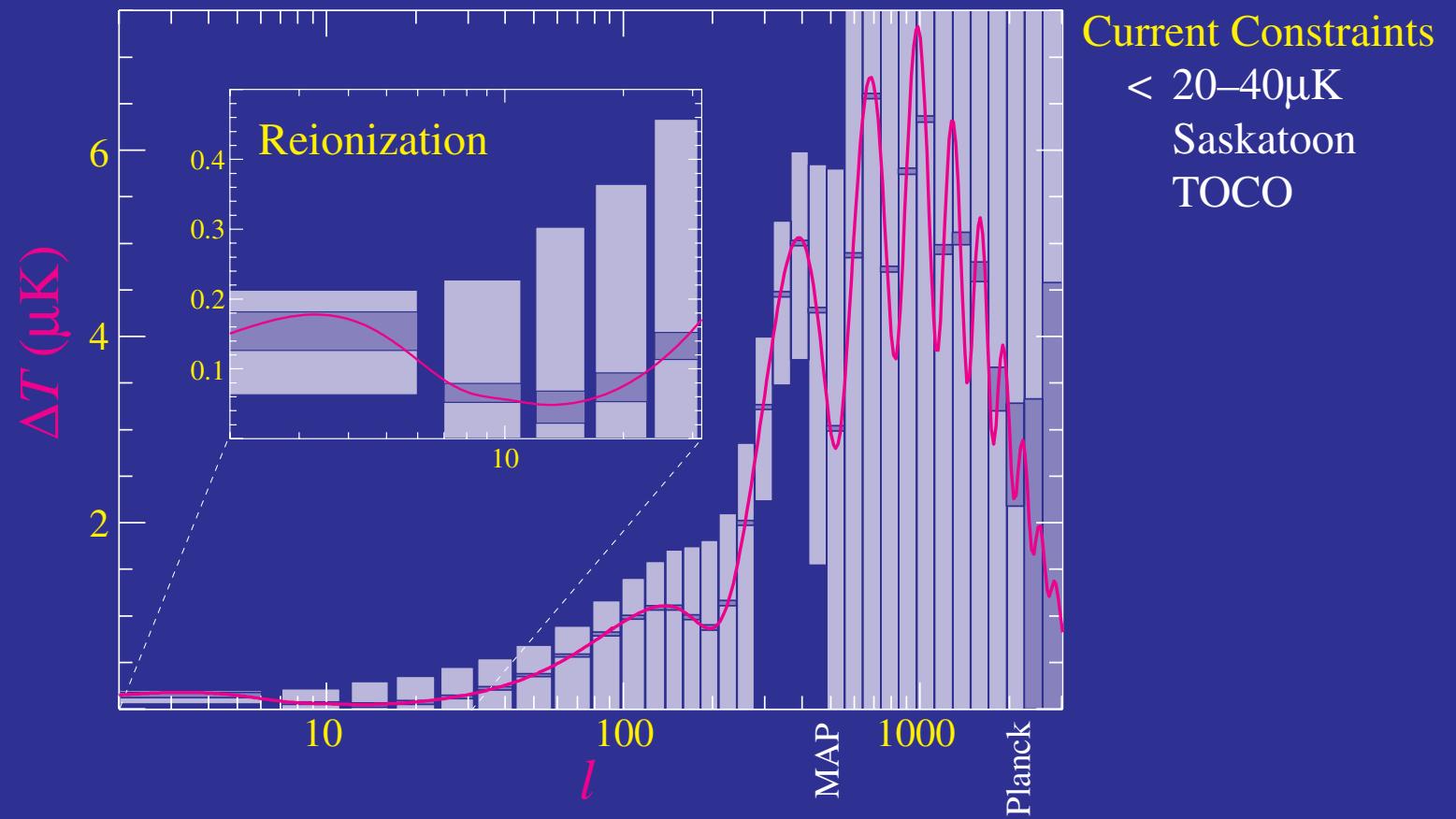
- CMB polarization generated by scattering of quadrupole anisotropies
- Isolates the last scattering surface  
→ tests causal generation (inflation vs. defects)



Hu & White (1997)  
Zaldarriaga & Spergel (1997)

# Polarization Diagnostics

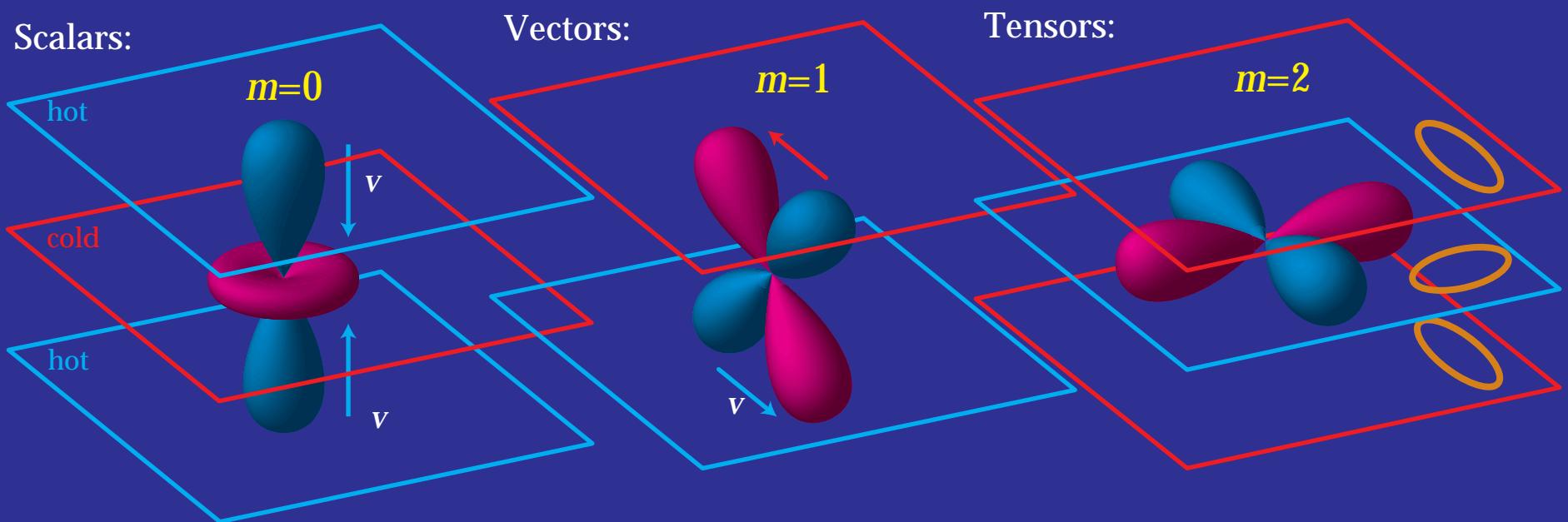
- CMB polarization generated by scattering of quadrupole anisotropies
- Isolates the last scattering surface  
→ measures the reionization epoch / optical depth (first structures)



Hogan, Kaiser, & Rees (1982)  
Efstathiou & Bond (1987)

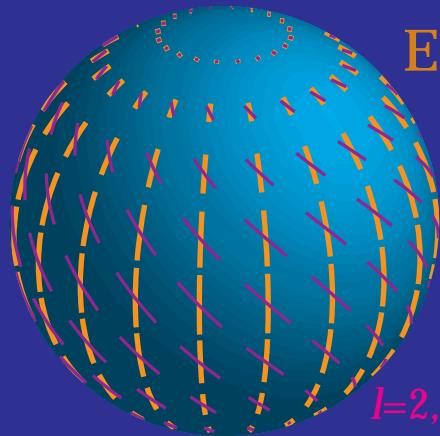
# Perturbations & Their Quadrupoles

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



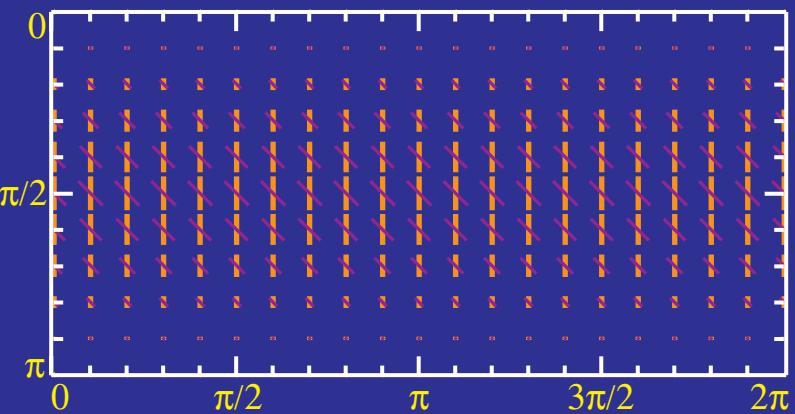
# Polarization Patterns

Scalars

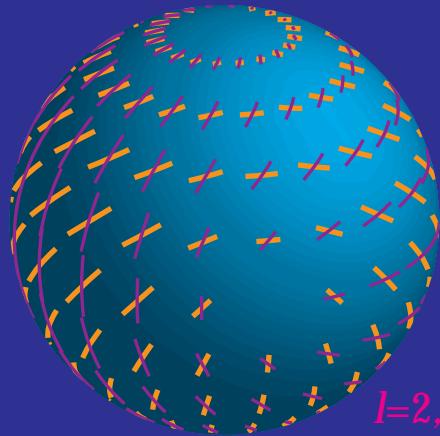


E, B

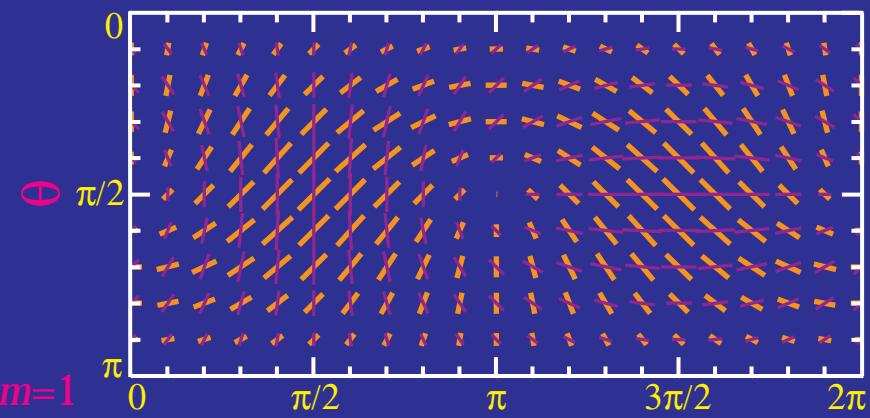
$l=2, m=0$



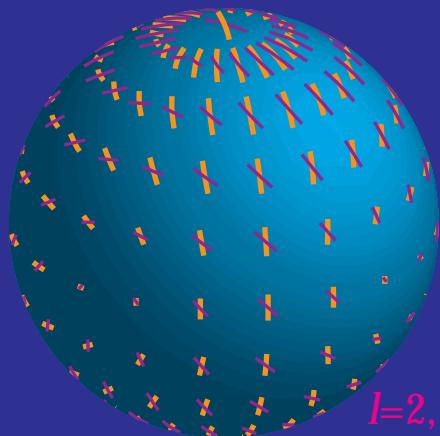
Vectors



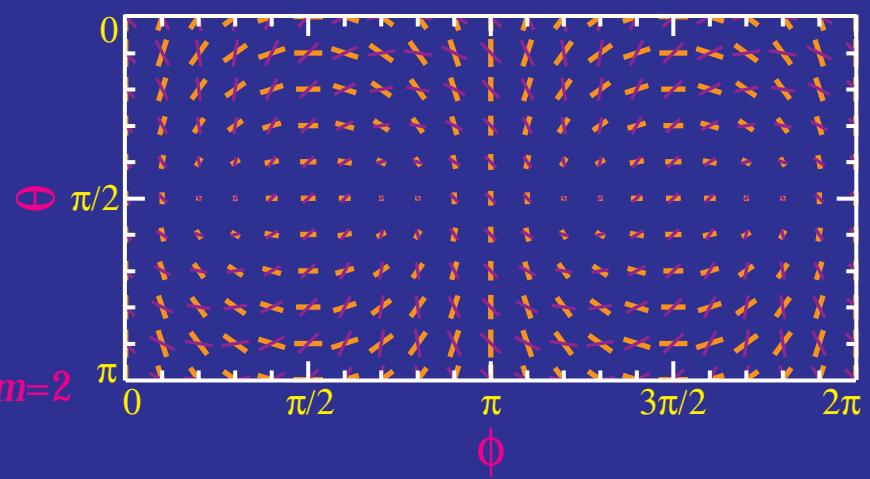
$l=2, m=1$



Tensors



$l=2, m=2$



**CMB**

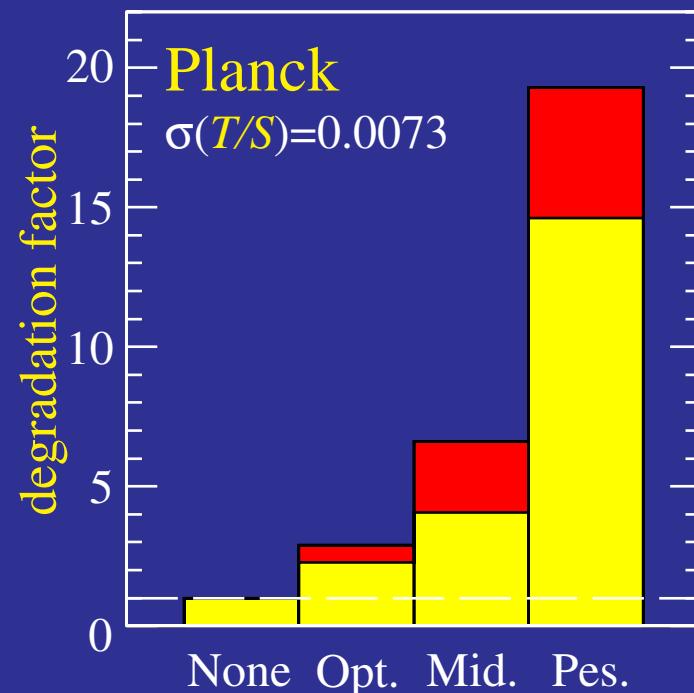
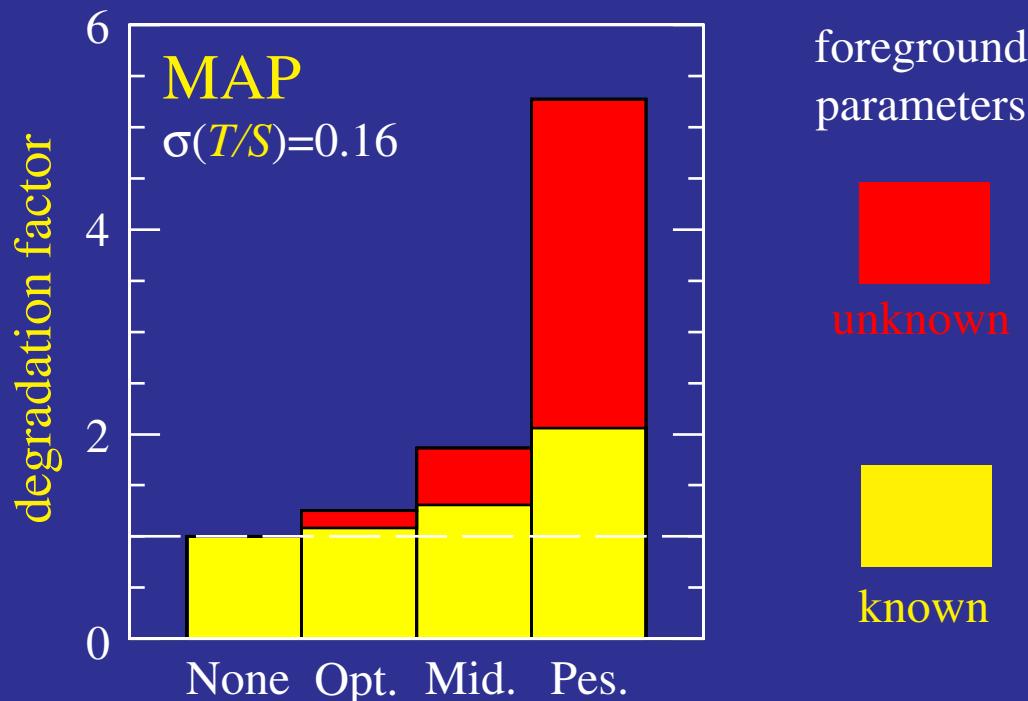
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# FOREGROUNDS

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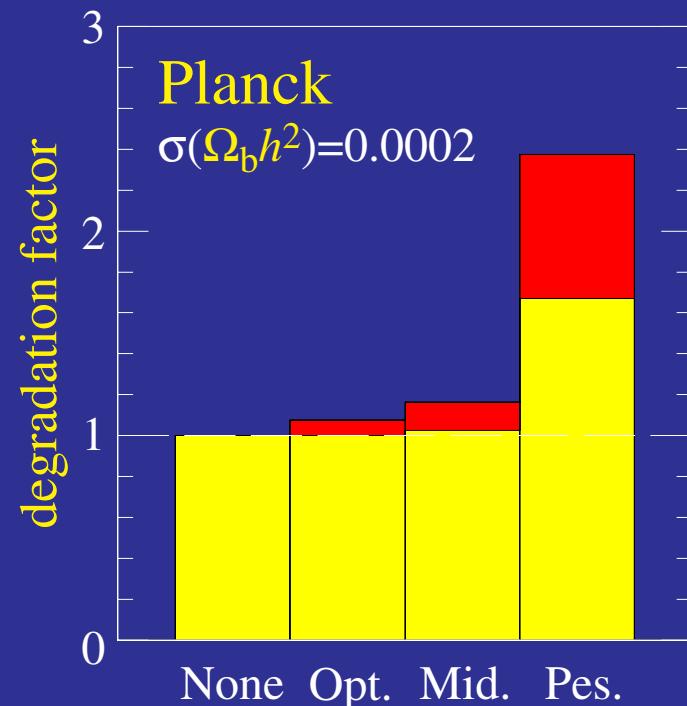
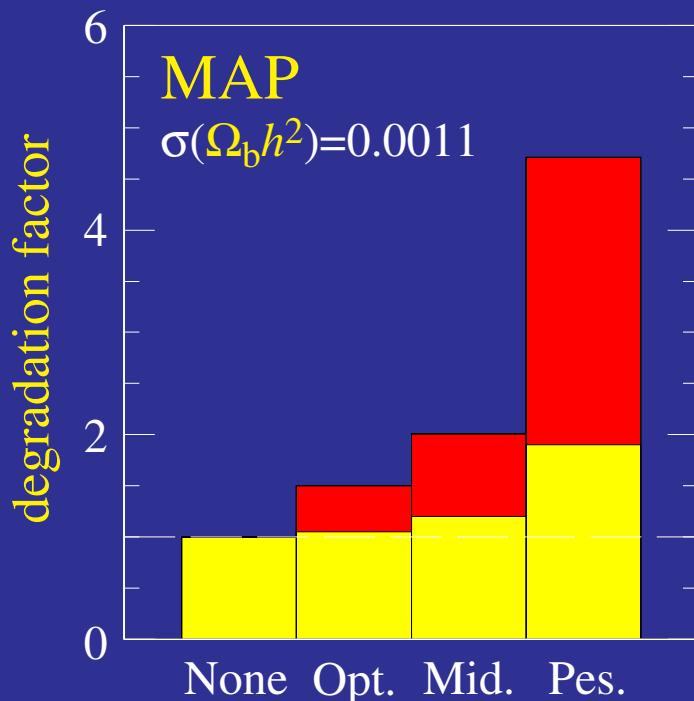
THE PHANTOM MENACE

# Foregrounds and Tensors



- 257–561 Foreground Parameters Simultaneously Estimated
- Foreground power spectra, frequency dependence, frequency coherence free-free, synchrotron, vibrating dust, rotating dust, thermal SZ, radio point sources, IR point sources
- 10 Cosmological Parameters
- Potentially significant degradation: better prior knowledge; more frequencies

# Foregrounds and Baryons



- 257–561 Foreground Parameters Simultaneously Estimated
- Foreground power spectra, frequency dependence, frequency coherence free-free, synchrotron, vibrating dust, rotating dust, thermal SZ, radio point sources, IR point sources
- 10 Cosmological Parameters
- Degradation of less than 2 in errors

# Summary

- Simple adiabatic CDM models have survived the onslaught of data to date
- The dark energy is not curvature
- Baryonic dark matter and low density cold dark matter indicated
- First peak location inconsistent with most non-inflationary models (unless universe is closed or recombination delayed)

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- Foregrounds not expected to be a problem for power spectrum estimation in the acoustic regime but will be a serious issue for polarization, sub-arcminute anisotropy and non-Gaussianity.

# Index

- Current CMB Data
- Future Missions
- Current Constraints
- Thermal History
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- Dark Baryons
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- Baryon Drag
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- Matter/Radiation
- Inflation
- Polarization
- Sensitivity
- Secondary Anisotropies
- Current Directions
- Phantom Menace
- Foregrounds & Tensors
- Foregrounds & Baryons

Complete Talk:  
<http://www.sns.ias.edu/~whu/resceu.pdf>

Outtakes