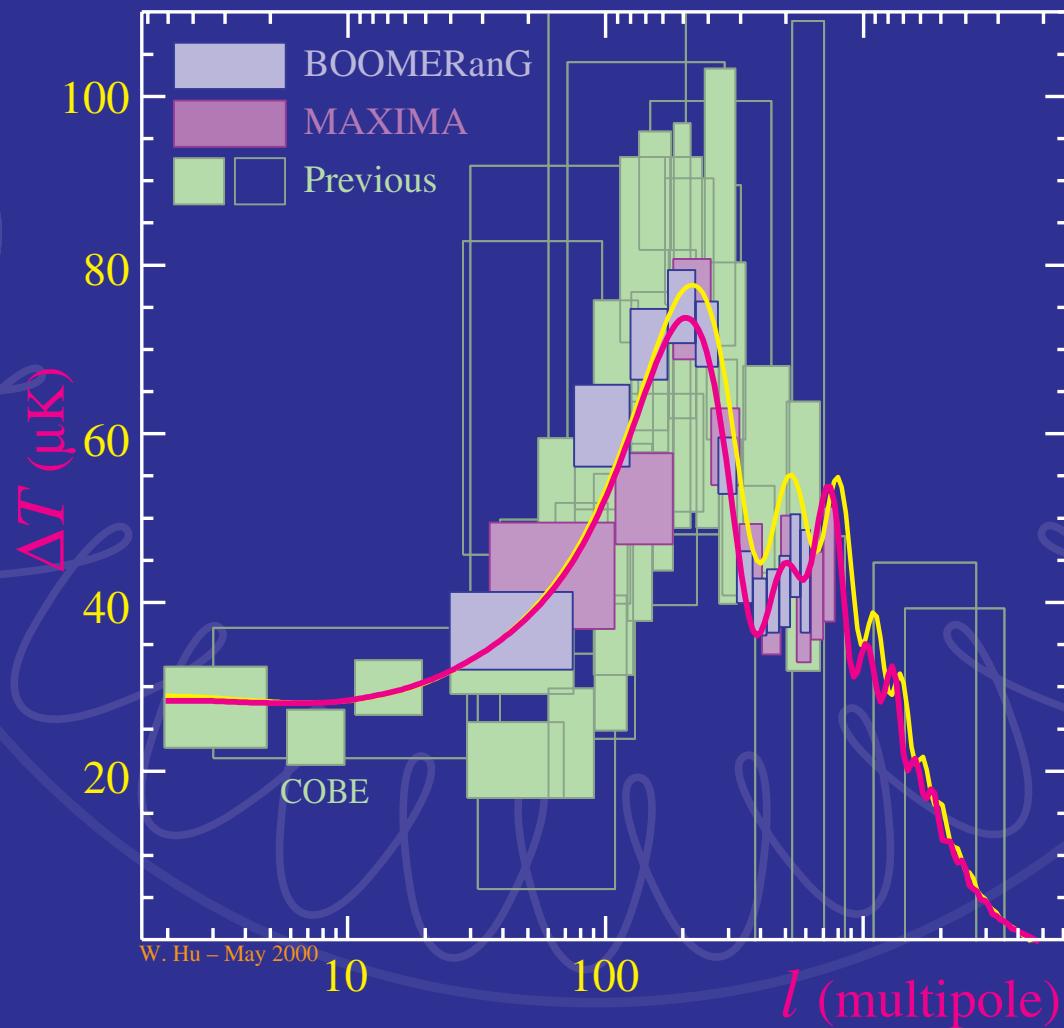


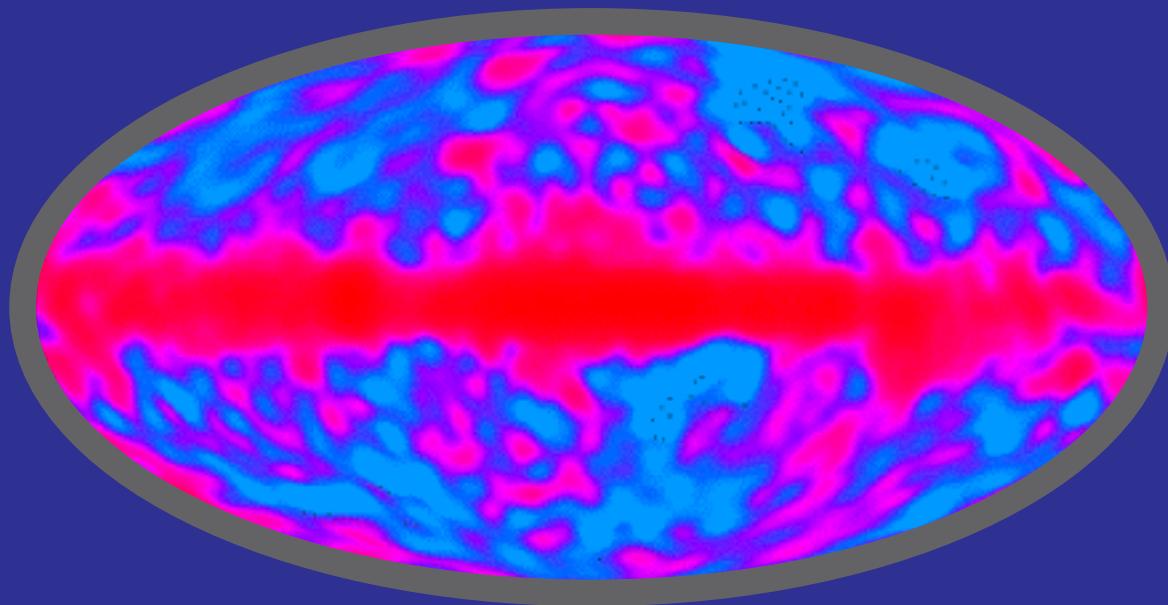
Ringing in the New Cosmology



DOE, June 2000

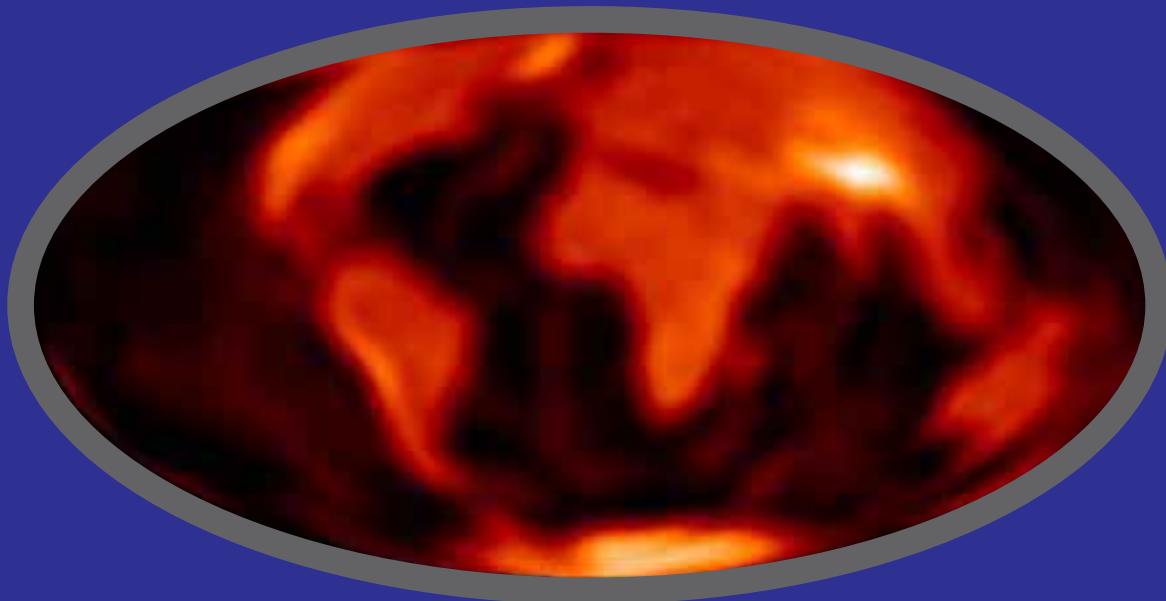
Wayne Hu

COBE Anisotropies



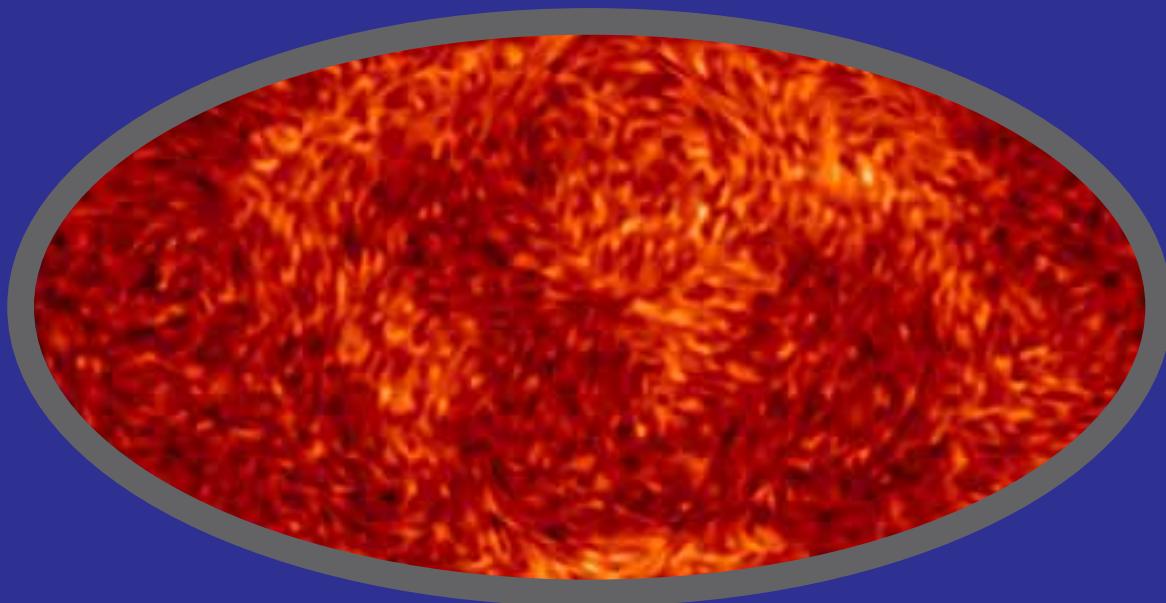
10° – 90° fluctuations

COBE Anisotropies



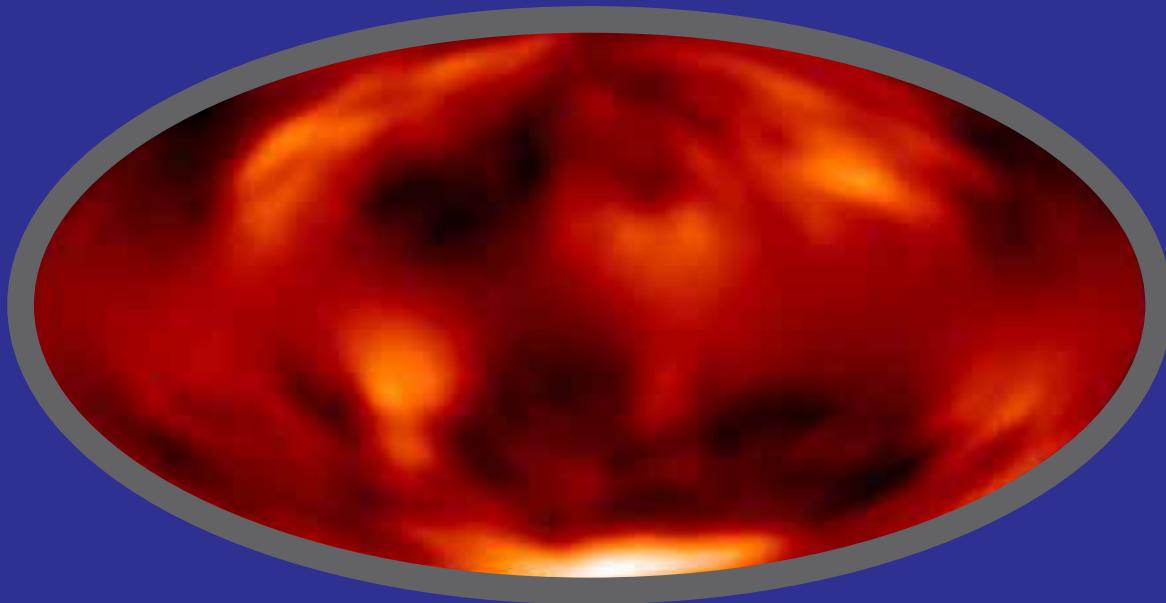
COBE 7° Beam

COBE Anisotropies



COBE Detector Noise

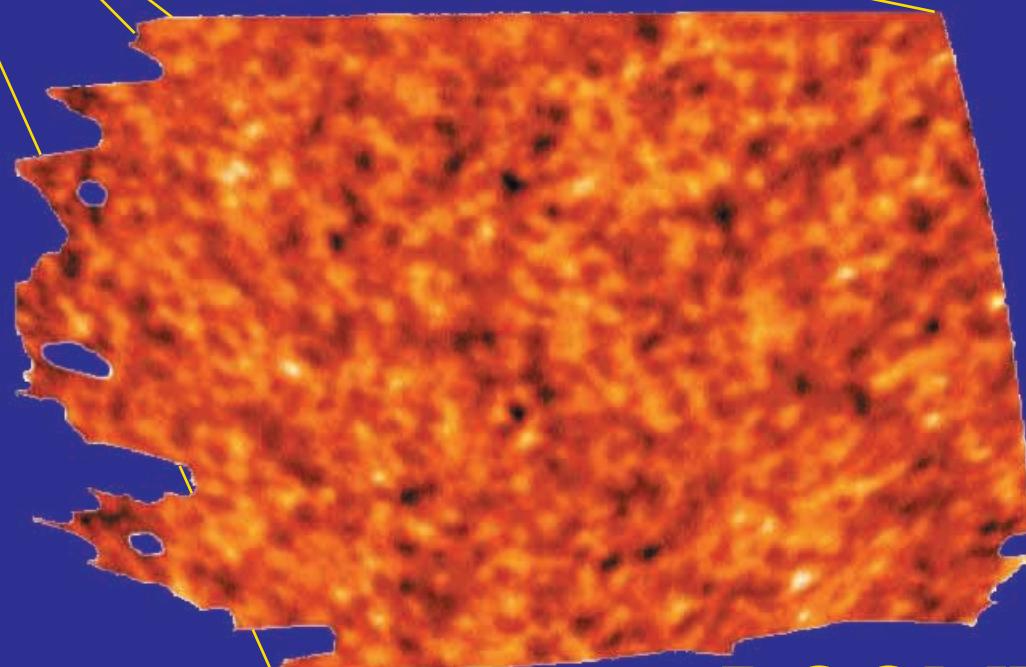
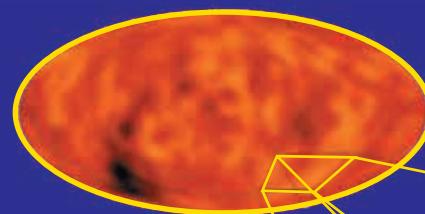
COBE Anisotropies



Filtered Map

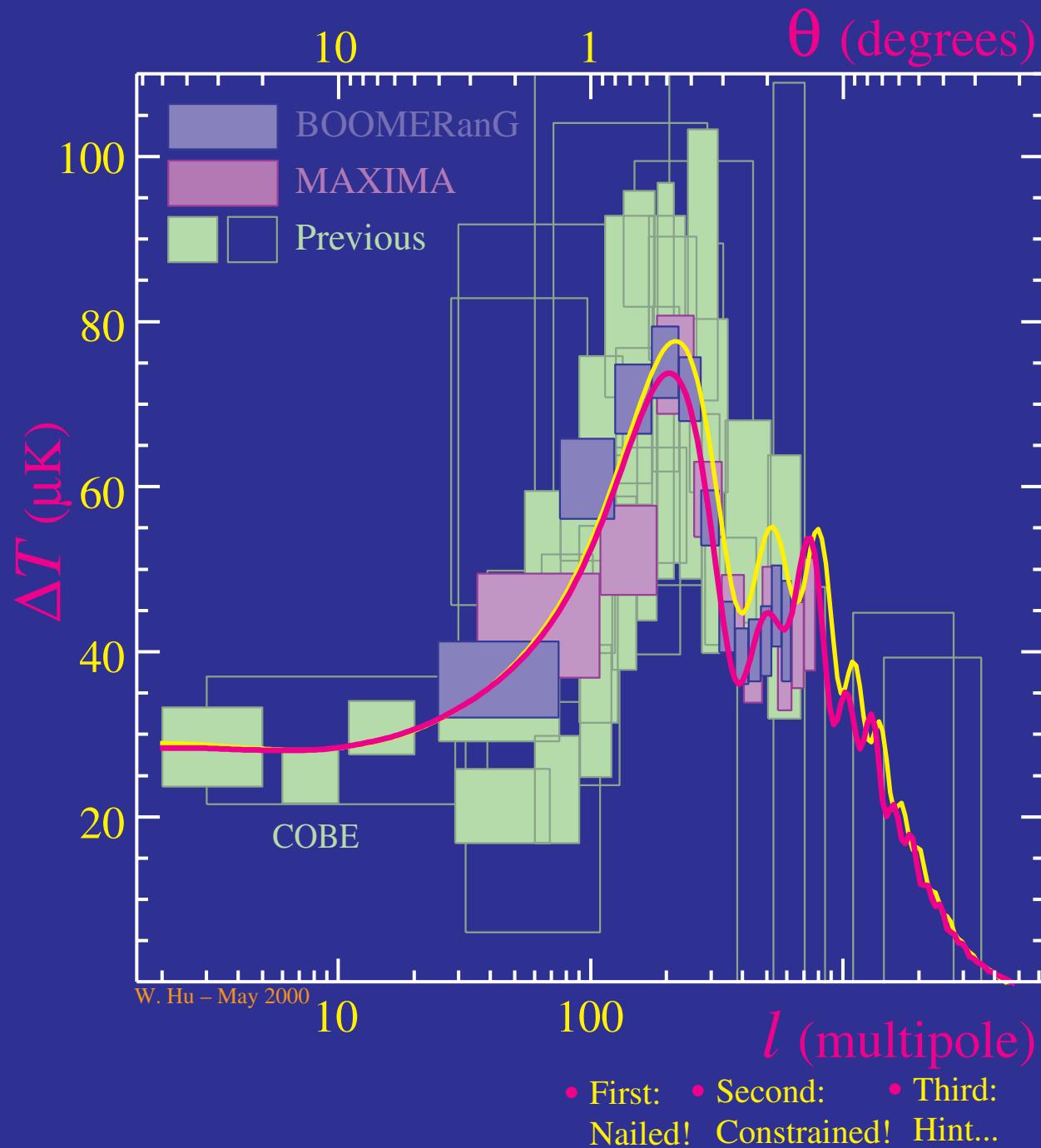
CMB Anisotropies

COBE



BOOMERanG

Sound Physics Seen



So What...

- Many multi-dimensional parameter studies performed (Lange et al., etc)
- Results depend on prior assumptions: get back to the observables!
- First peak (surprise: 5-10% larger angular scale)

Shape: inflationary origin of perturbations

Location: spatial curvature
dark matter density (lower limit if flat)
equation of state of dark energy \sim age

Height: inflationary spectrum (tilt, lower limit with 2nd)

- Second Peak (surprise: low amplitude)

Relative height: baryon density (lower limit)
inflationary spectrum (tilt, gravity wave implications)

- Third Peak (note: not very high)

Relative height: dark matter density (upper limit)

Acoustic Oscillations



Thermal History

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

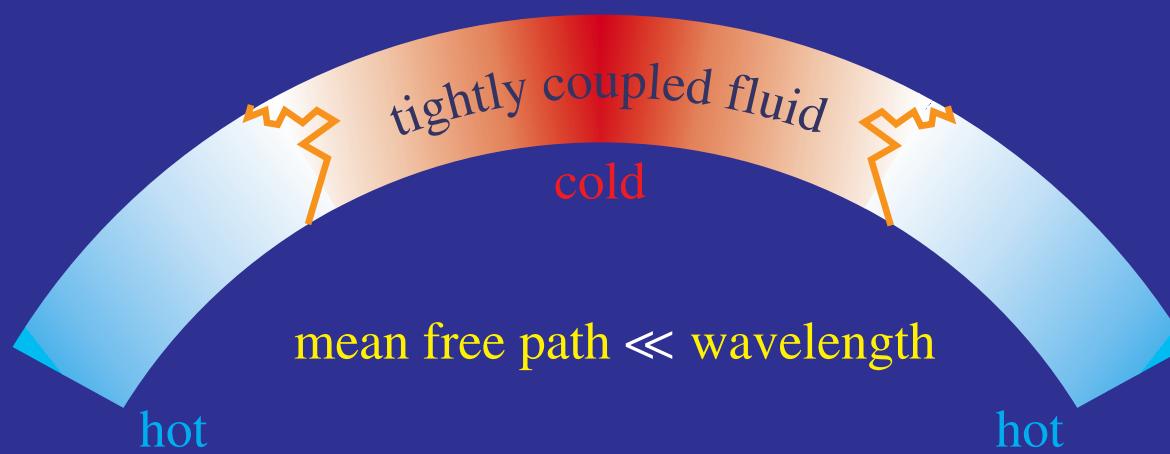
Hydrogen ionized

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

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

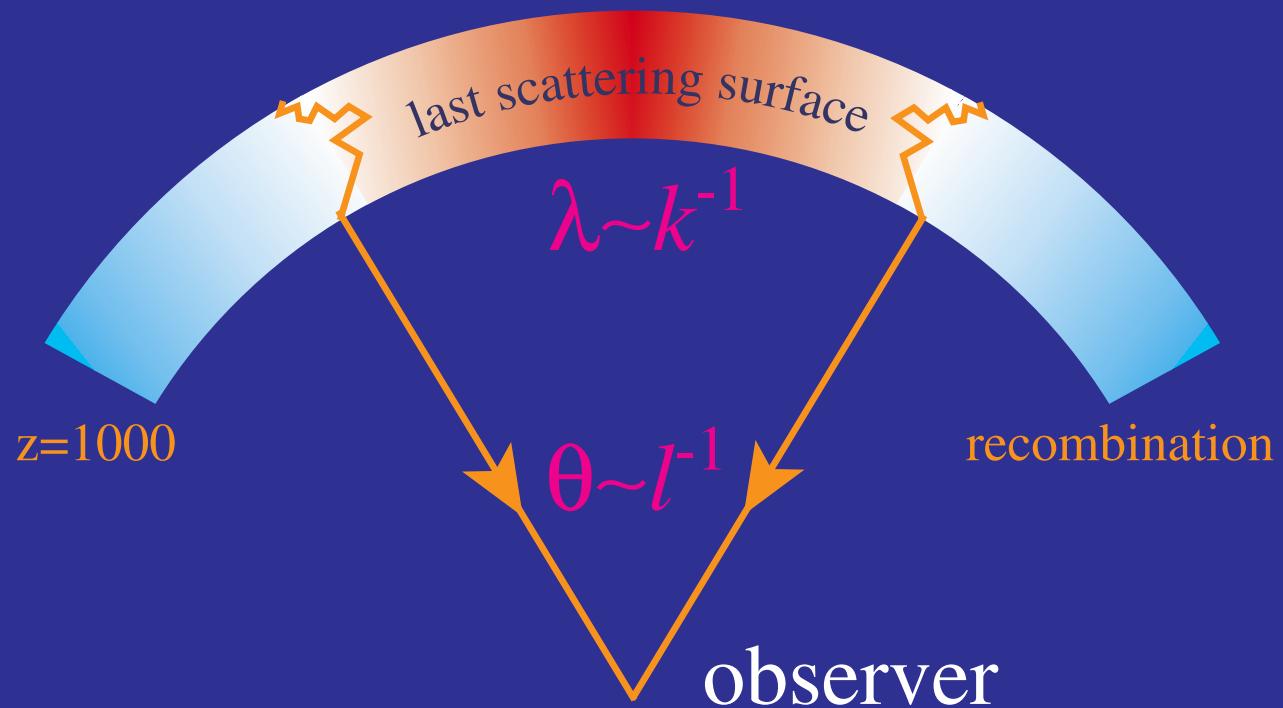
Recombination

Fluid breakdown

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

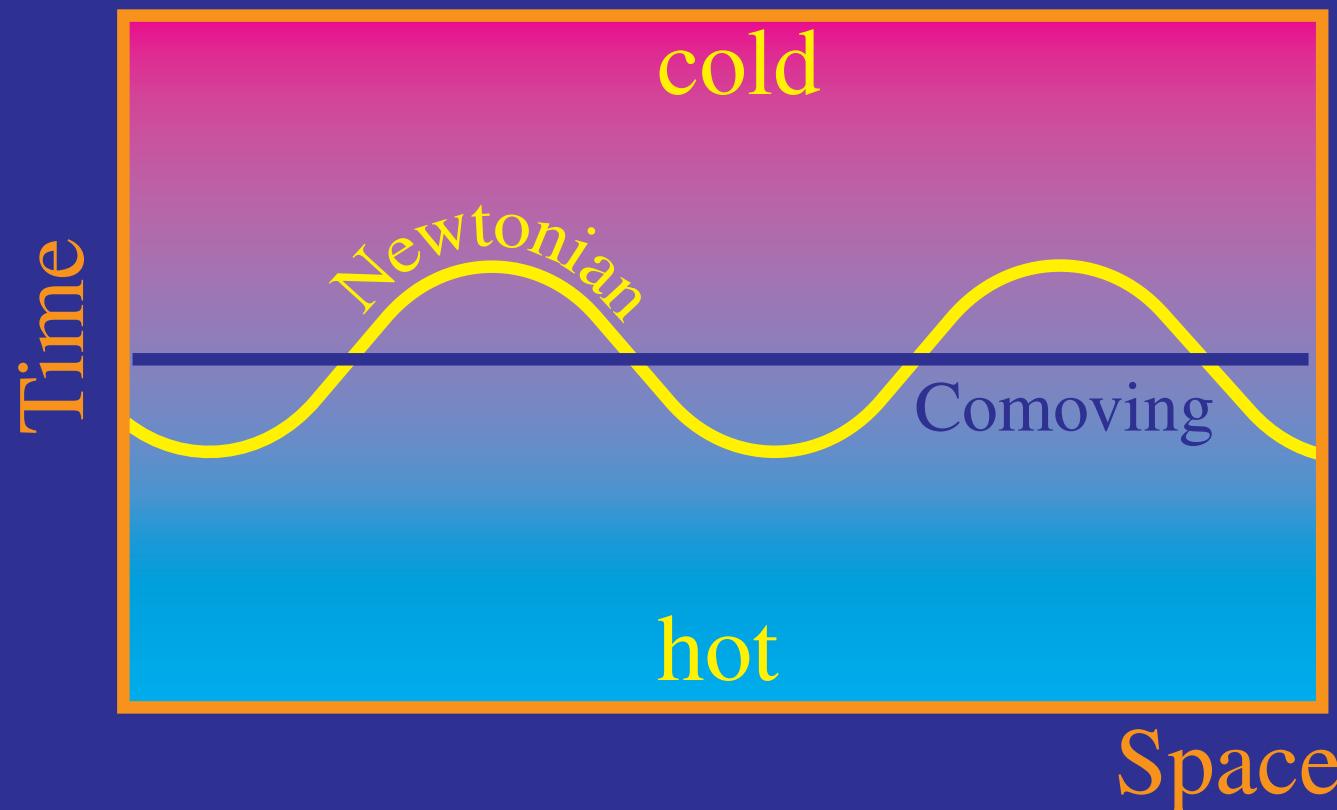
Gravitational redshifts &
lensing

Reionization; rescattering



Inflation and the Initial Conditions

- Inflation: (nearly) scale-invariant curvature (potential) perturbations
- Superluminal expansion \rightarrow superhorizon scales \rightarrow "initial conditions"
- Accompanying temperature perturbations due to cosmological redshift

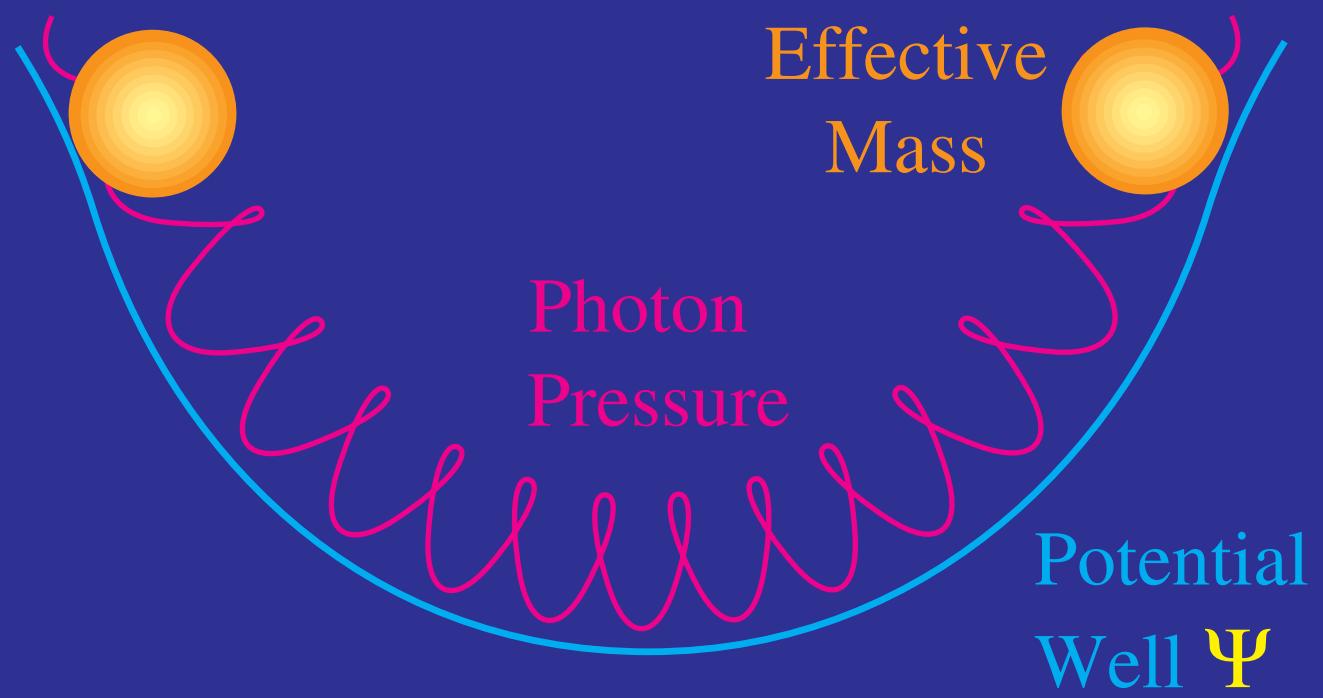


- Potential perturbation $\Psi = \text{time-time metric perturbation}$
 $\delta t/t = \Psi \quad \rightarrow \quad \delta T/T = -\delta a/a = -2/3 \delta t/t = -2/3 \Psi$

Sachs & Wolfe (1967); White & Hu (1997)

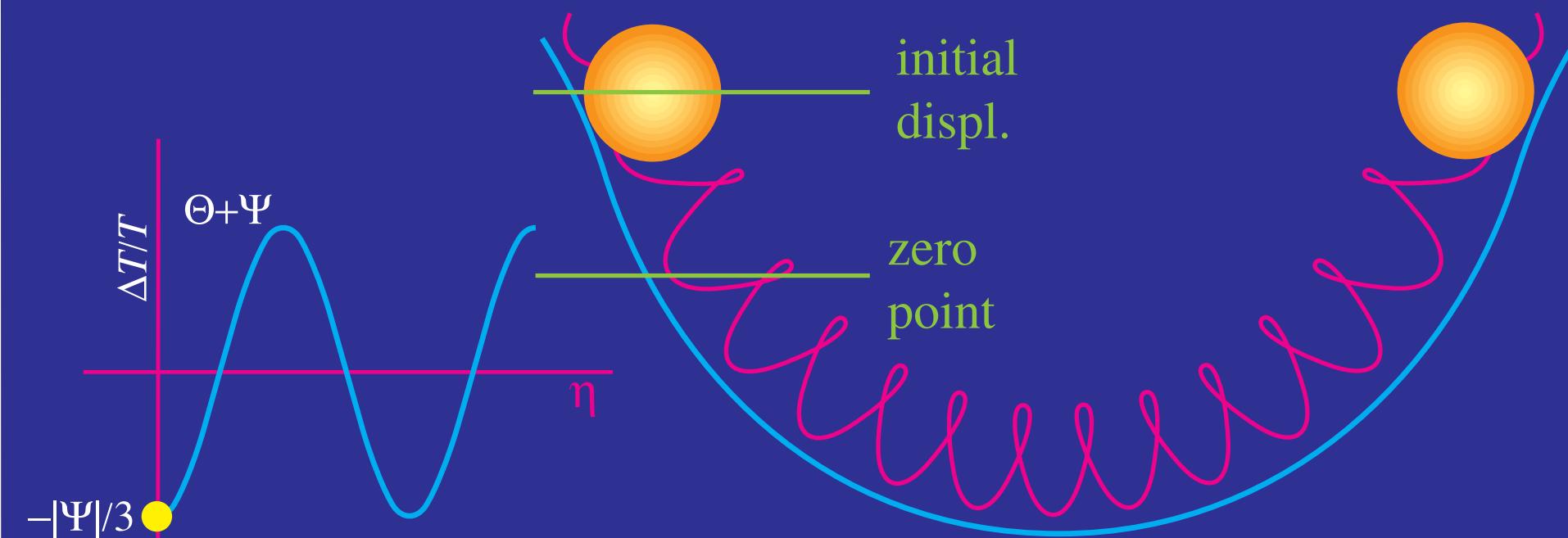
Acoustic Oscillations

- Photon pressure resists compression in potential wells
- Acoustic oscillations



Acoustic Oscillations

- Photon pressure resists compression in potential wells
- Acoustic oscillations
- Gravity displaces zero point
 $\Theta \equiv \delta T/T = -\Psi$
- Oscillation amplitude = initial displacement from zero pt.
 $\Theta - (-\Psi) = 1/3\Psi$

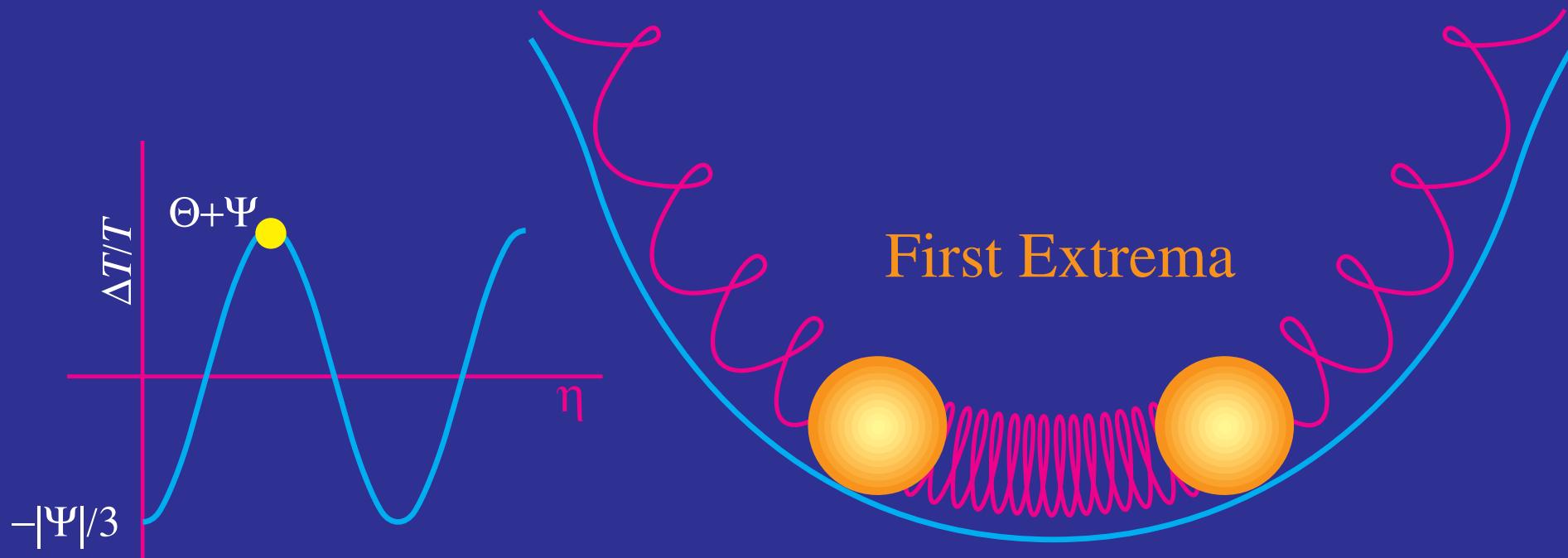


Peebles & Yu (1970)

Hu & Sugiyama (1995)

Acoustic Oscillations

- Photon pressure resists compression in potential wells
- Acoustic oscillations
- Gravity displaces zero point
 $\Theta \equiv \delta T/T = -\Psi$
- Oscillation amplitude = initial displacement from zero pt.
 $\Theta - (-\Psi) = 1/3\Psi$
- Gravitational redshift: observed
 $(\delta T/T)_{\text{obs}} = \Theta + \Psi$
oscillates around zero



Peebles & Yu (1970)

Hu & Sugiyama (1995)

Acoustic Oscillations

- Photon pressure resists compression in potential wells
- Acoustic oscillations
- Gravity displaces zero point
 $\Theta \equiv \delta T/T = -\Psi$
- Oscillation amplitude = initial displacement from zero pt.
 $\Theta - (-\Psi) = 1/3\Psi$
- Gravitational redshift: observed
 $(\delta T/T)_{\text{obs}} = \Theta + \Psi$
oscillates around zero

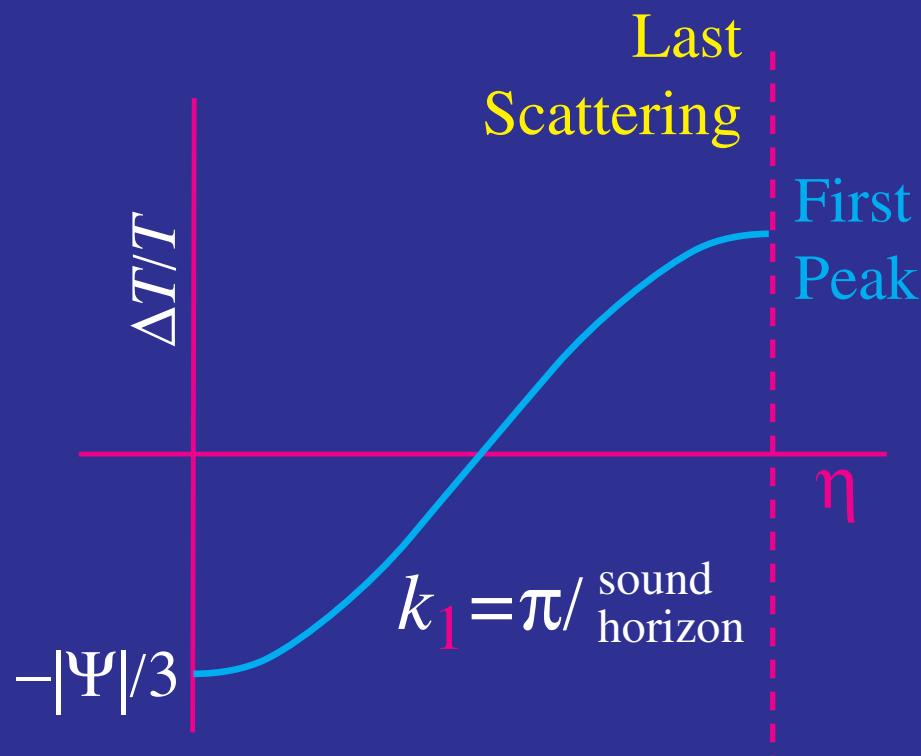


Peebles & Yu (1970)

Hu & Sugiyama (1995)

Harmonic Peaks

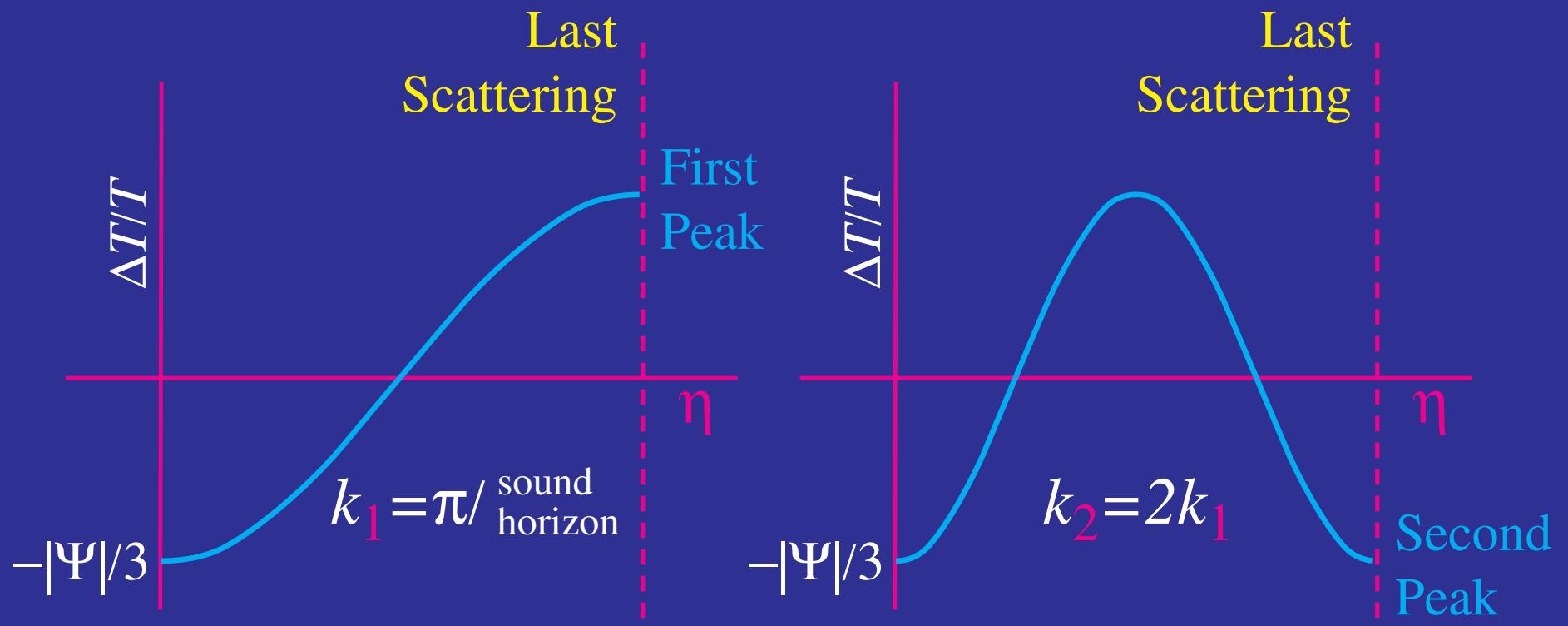
- Oscillations frozen at last scattering
- Wavenumbers at extrema = peaks
- Sound speed c_s



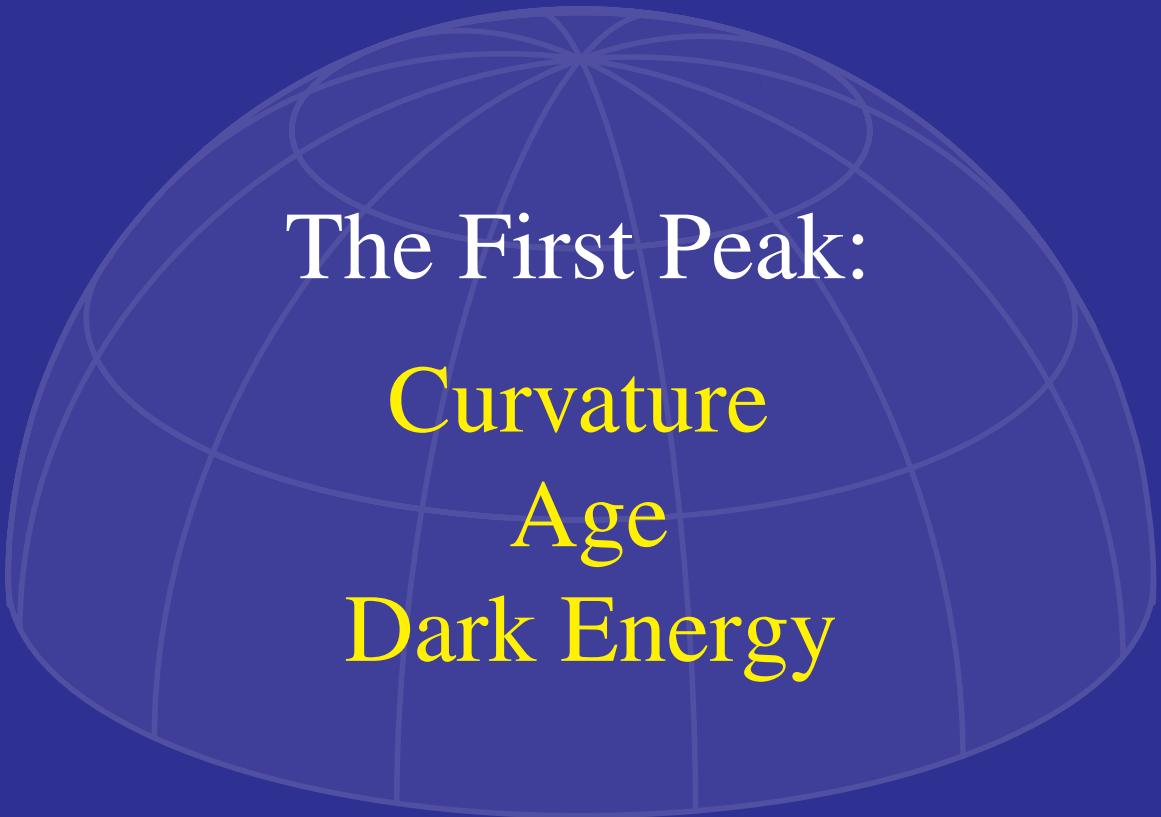
Doroshkevich, Zel'dovich & Sunyaev (1978); Bond & Efstathiou (1984); Hu & Sugiyama (1995)

Harmonic Peaks

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



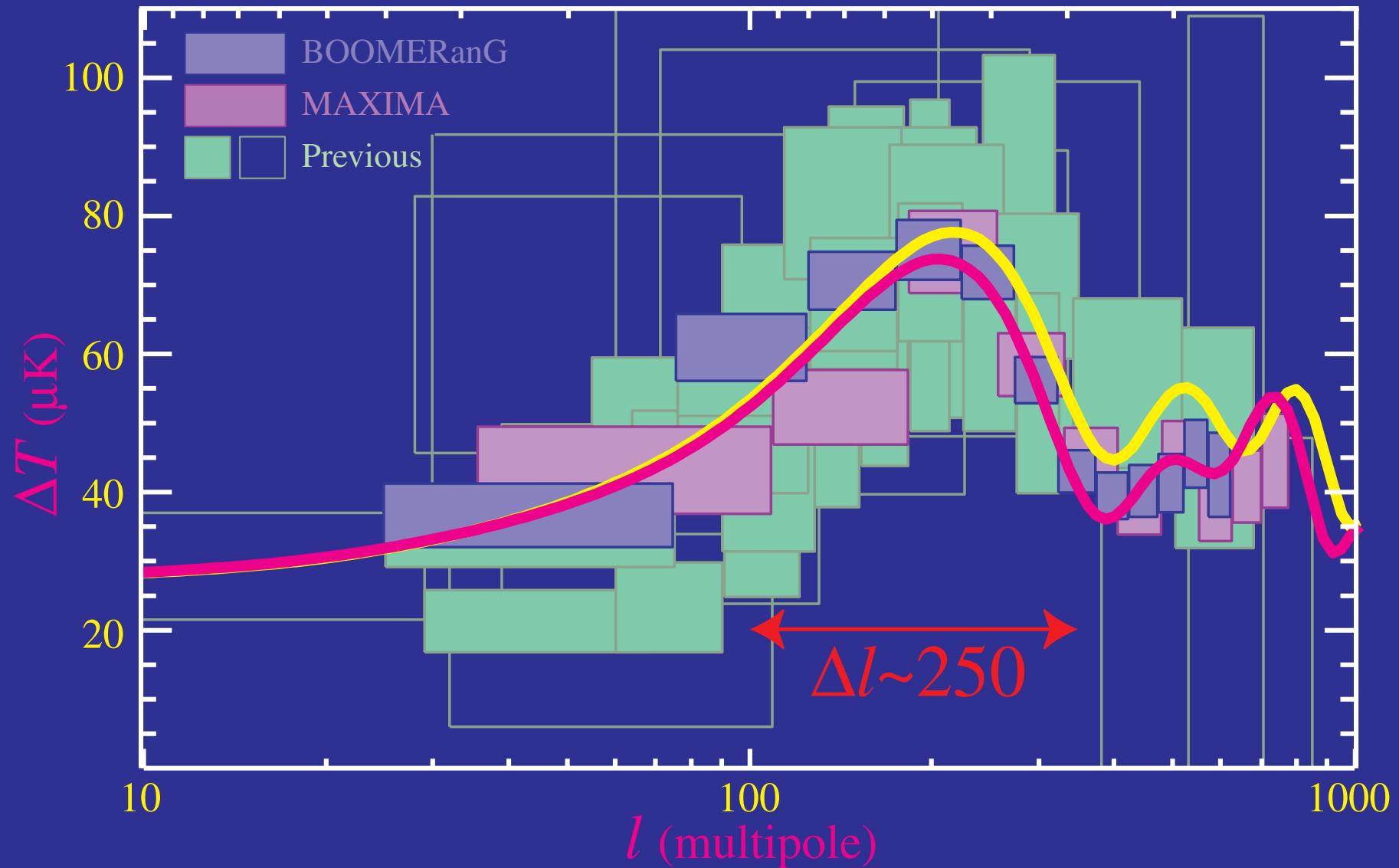
Doroshkevich, Zel'dovich & Sunyaev (1978); Bond & Efstathiou (1984); Hu & Sugiyama (1995)



The First Peak:
Curvature
Age
Dark Energy

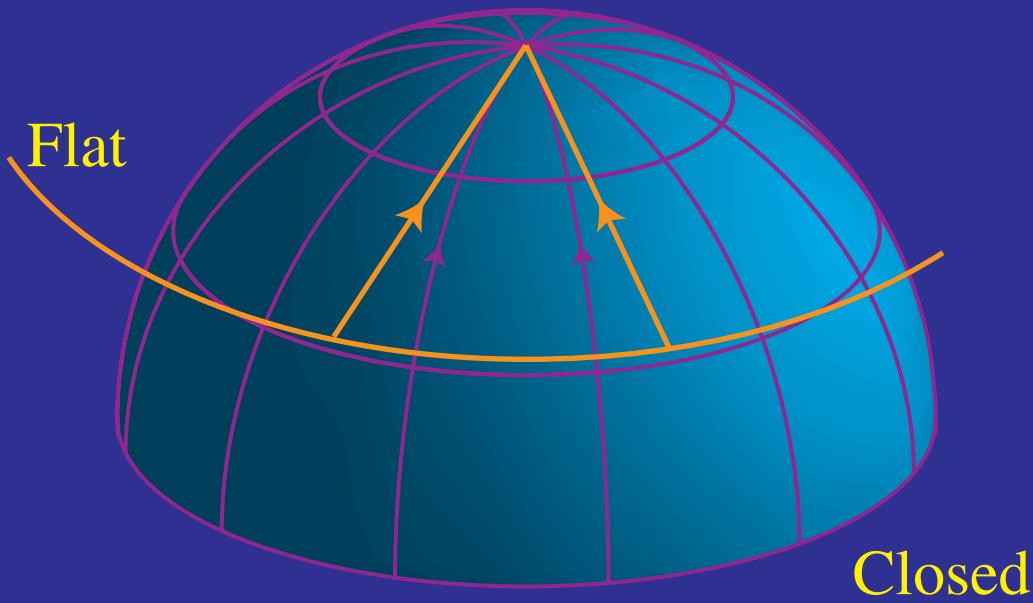
Shape of the First Peak

- Consistent with potential wells in place on superhorizon scale (inflation)
- Sharp fall from first peak indicates no continuous generation (defects)



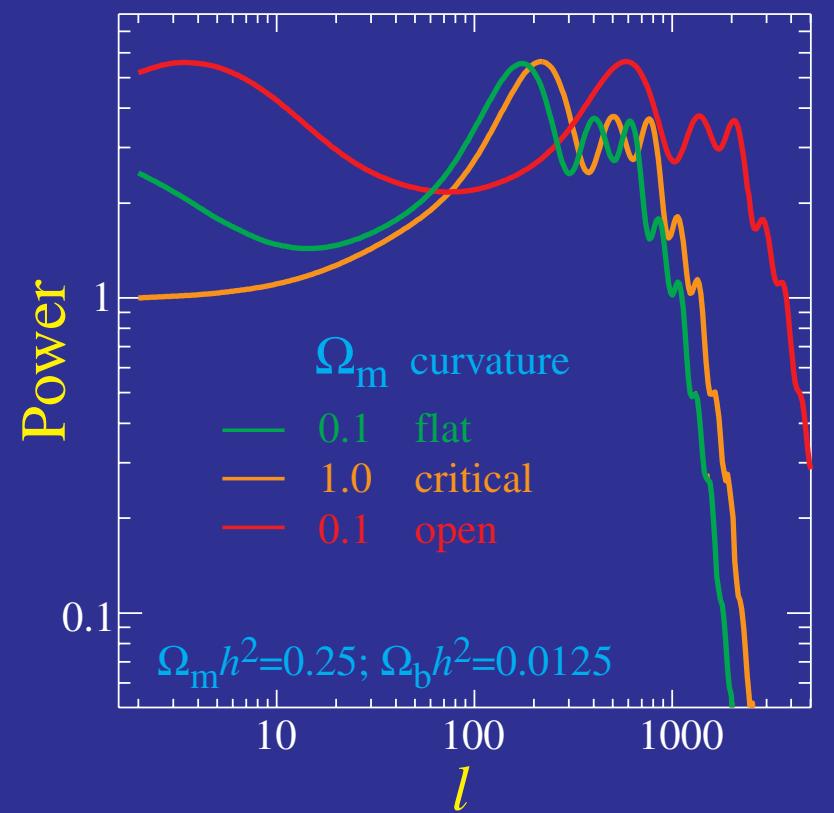
Angular Diameter Distance

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

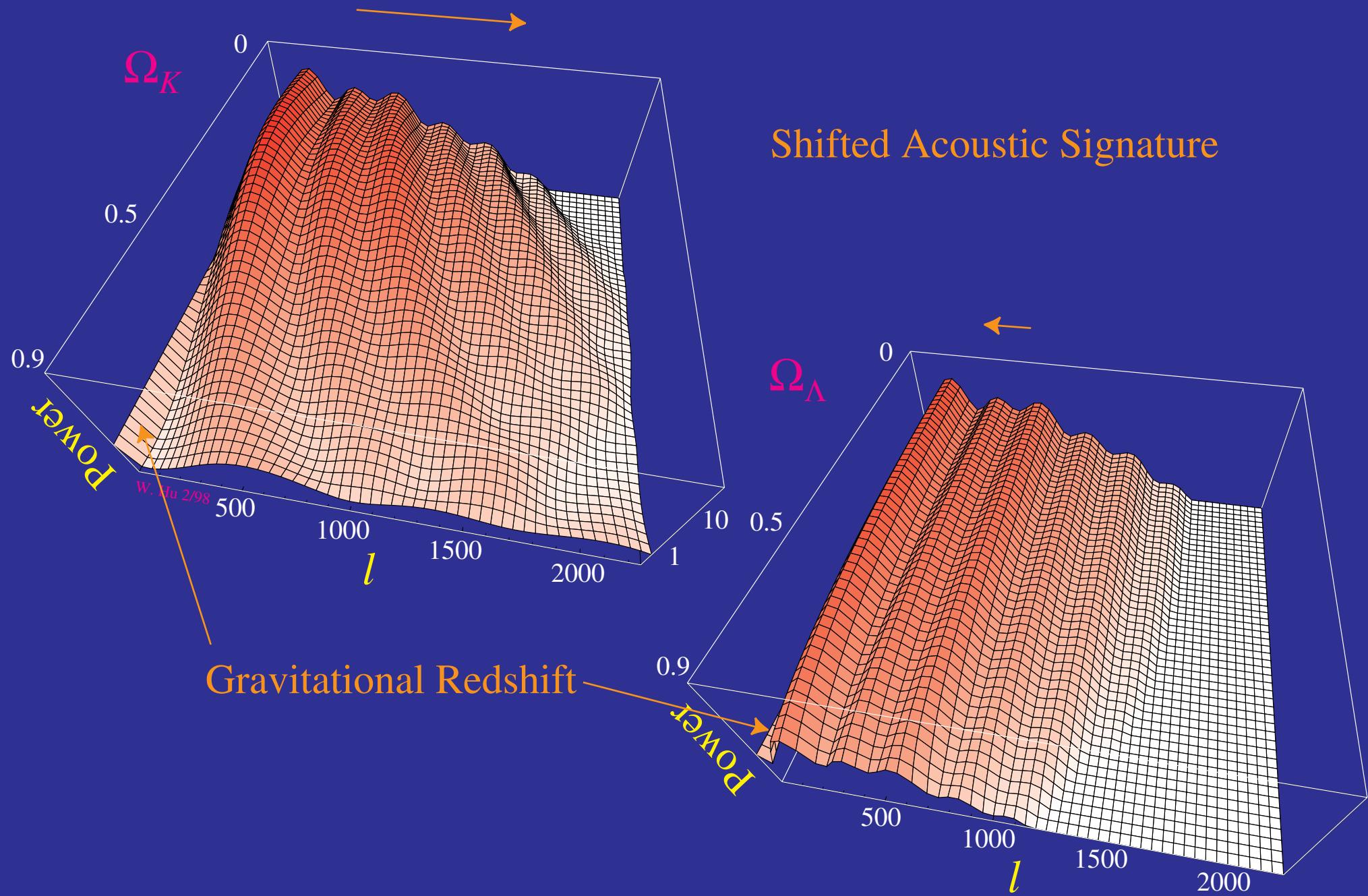


Kamionkowski, Spergel & Sugiyama (1994)
Hu & White (1996)

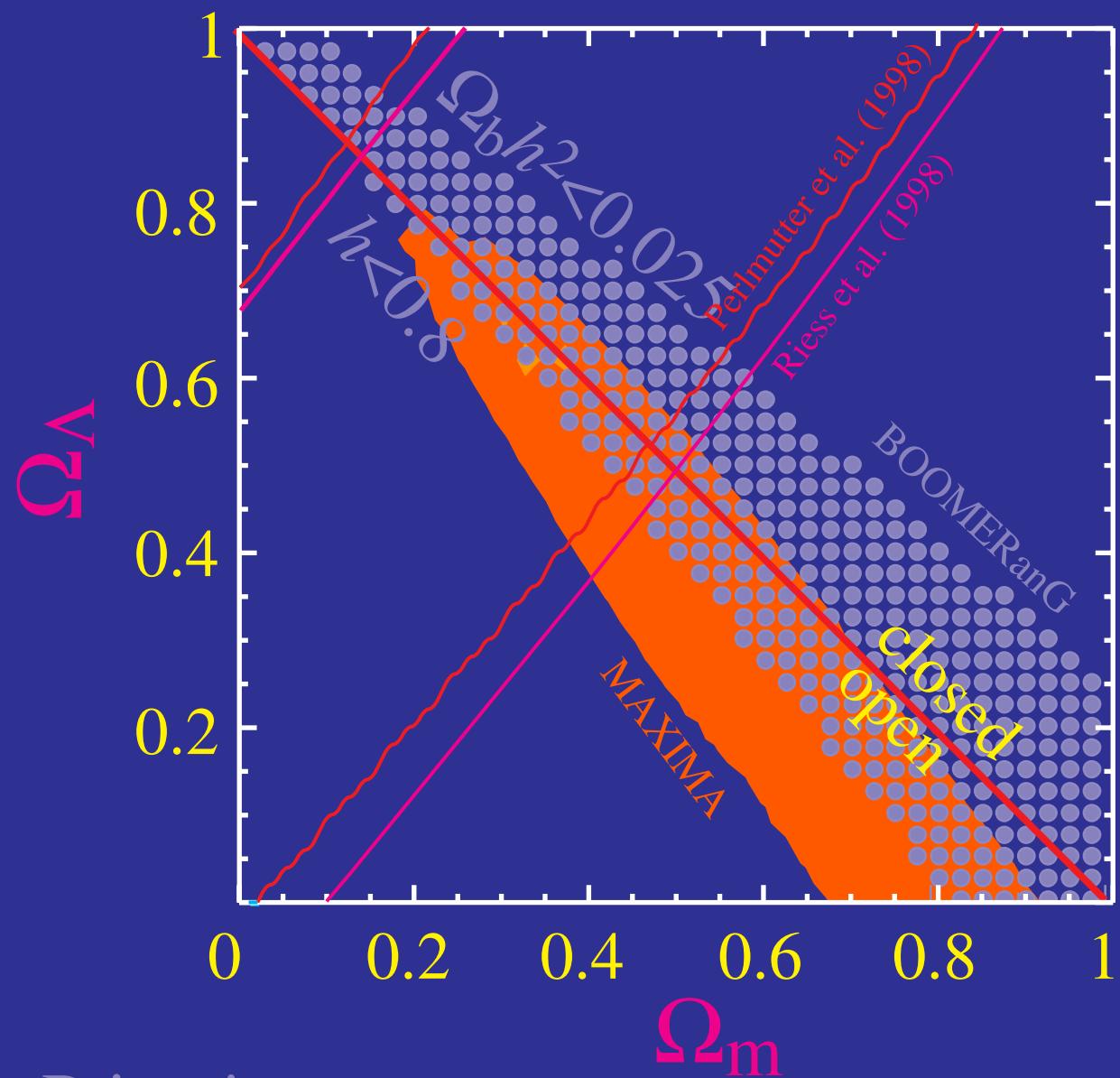
- Upper limit 1st Peak Scale (Horizon)
Upper limit on Curvature
- Calibrate 2 Physical Scales
 - Sound horizon (peak spacing) $\Omega_m h^2$ IC's
 - Diffusion scale (damping tail) $\Omega_b h^2$



Curvature and the Cosmological Constant



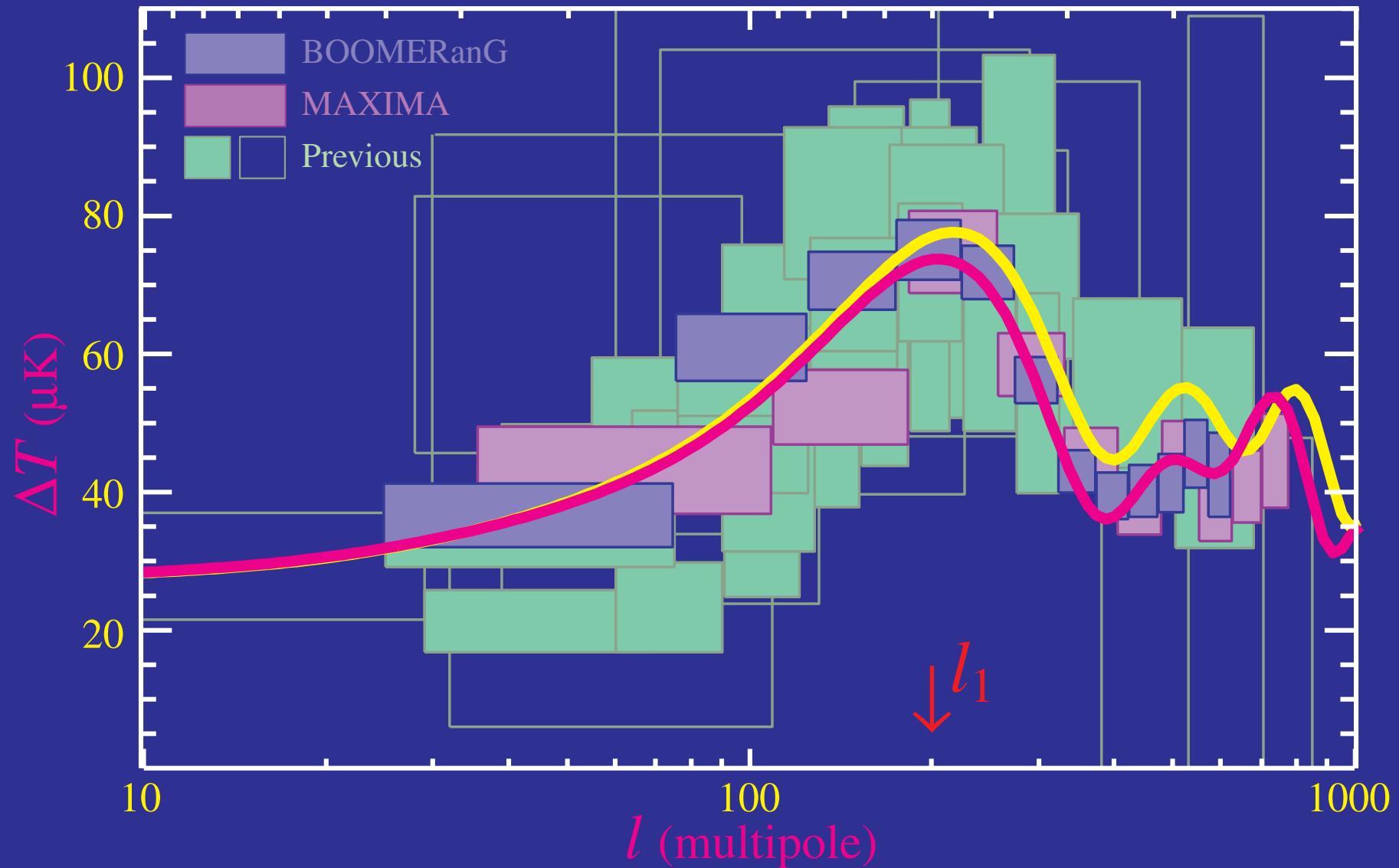
A Flat Universe!...?



Priors!

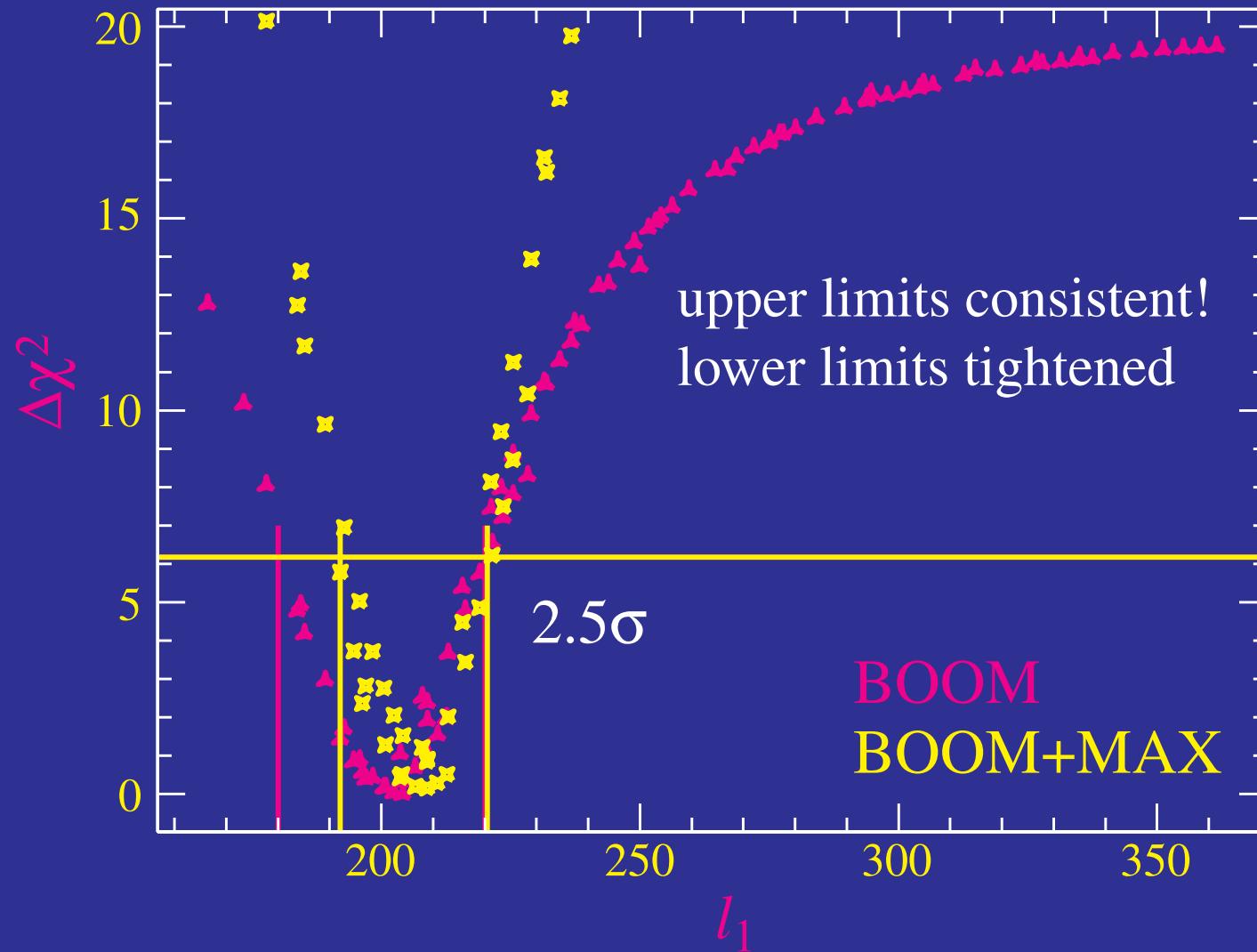
First Peak Location

- BOOM's parabolic peak fit $185 < l_1 < 209$ (2σ)
- MAX's value $l_1 \sim 220$



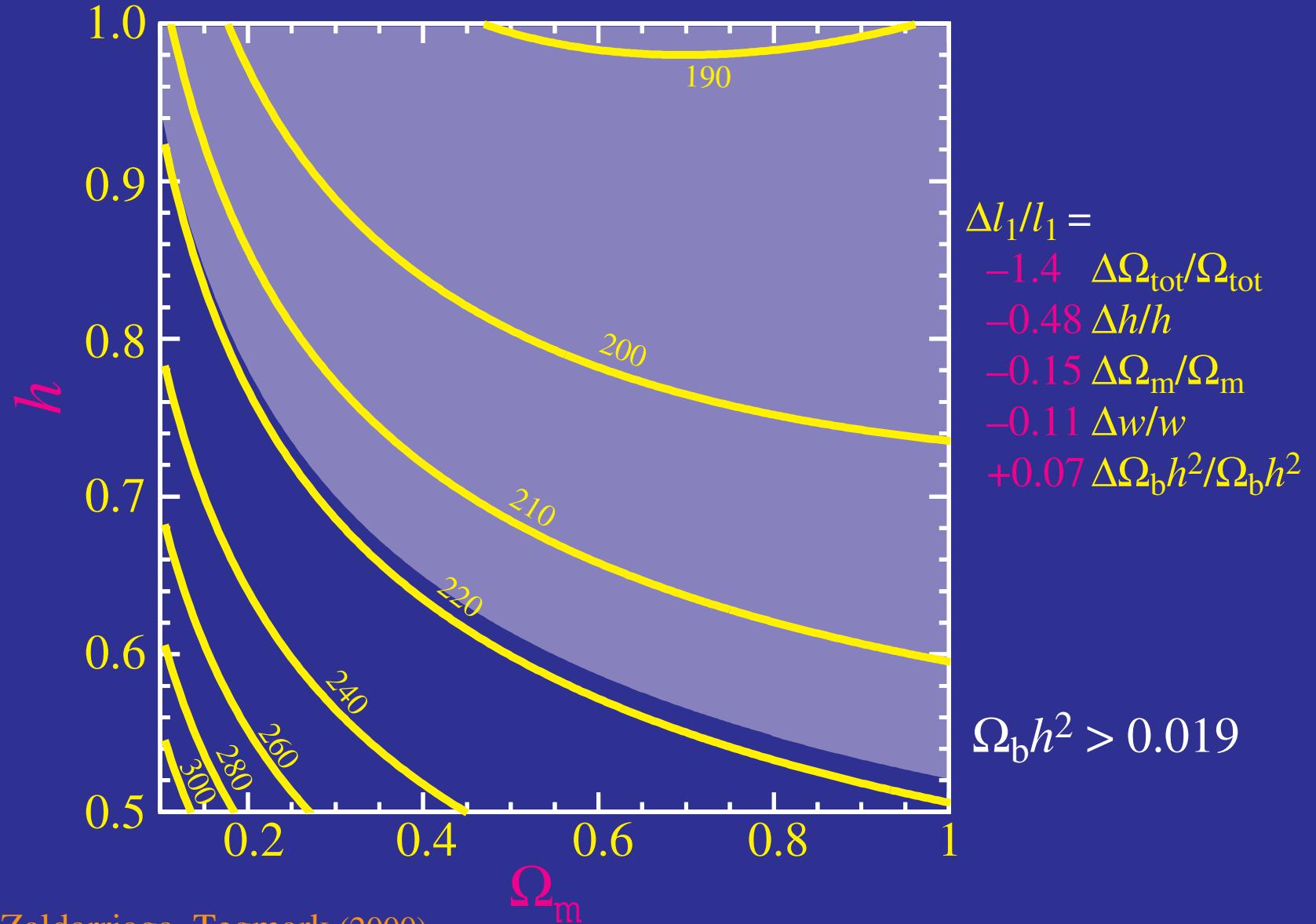
Are They Consistent?

- Using Λ CDM models: $184 < l_1 < 216$ (2σ ; BOOM)
- Joint analysis: $194 < l_1 < 218$ (2σ ; BOOM+MAX)



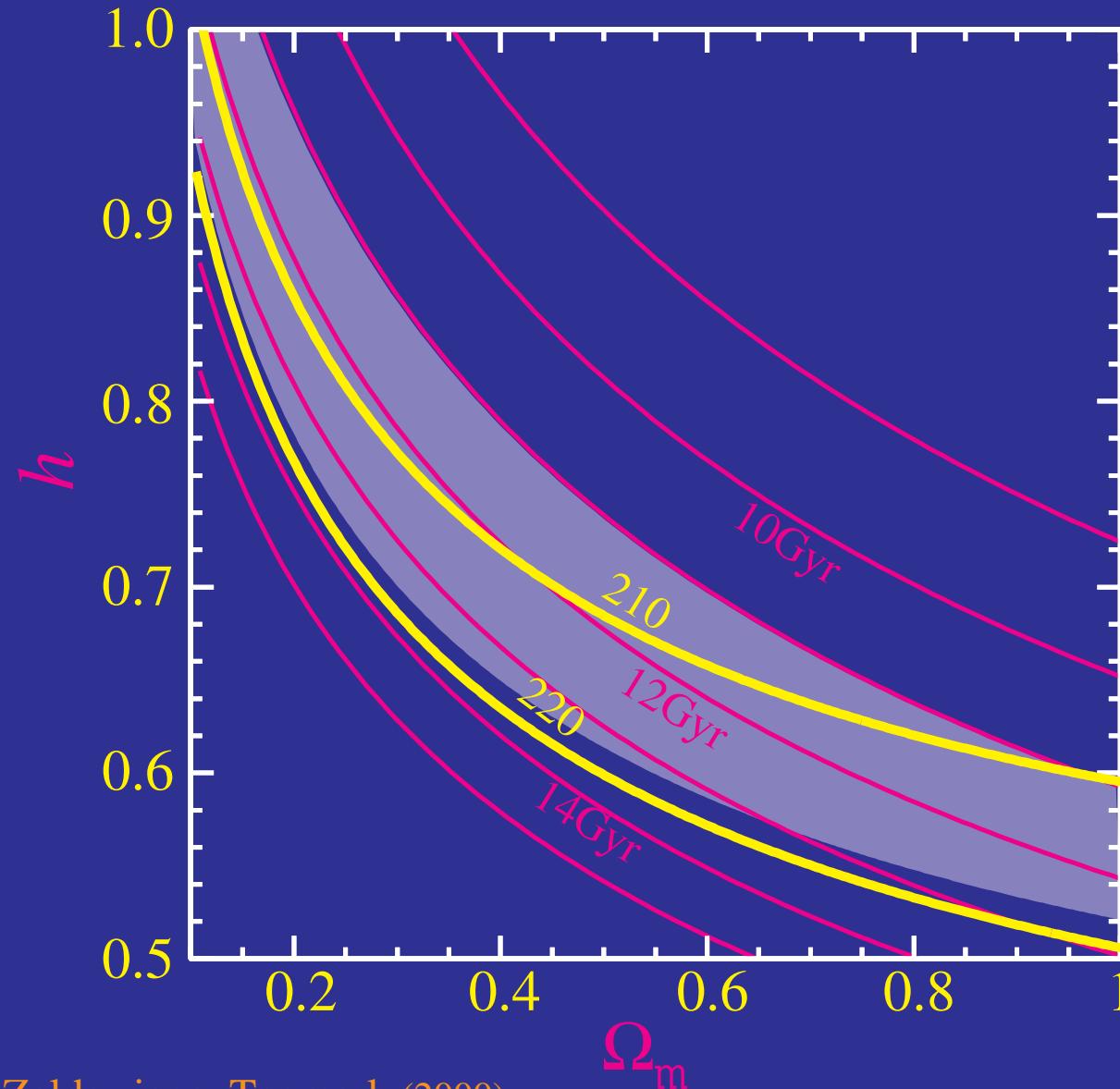
Is the Scale too Large?

- Fiducial flat $\Omega_m=0.35$, $h=0.65$ model: $l_1=221$ (excluded at $\sim 2.5\sigma$)
(a) positive curvature (b) high Hubble constant / matter (c) dark energy



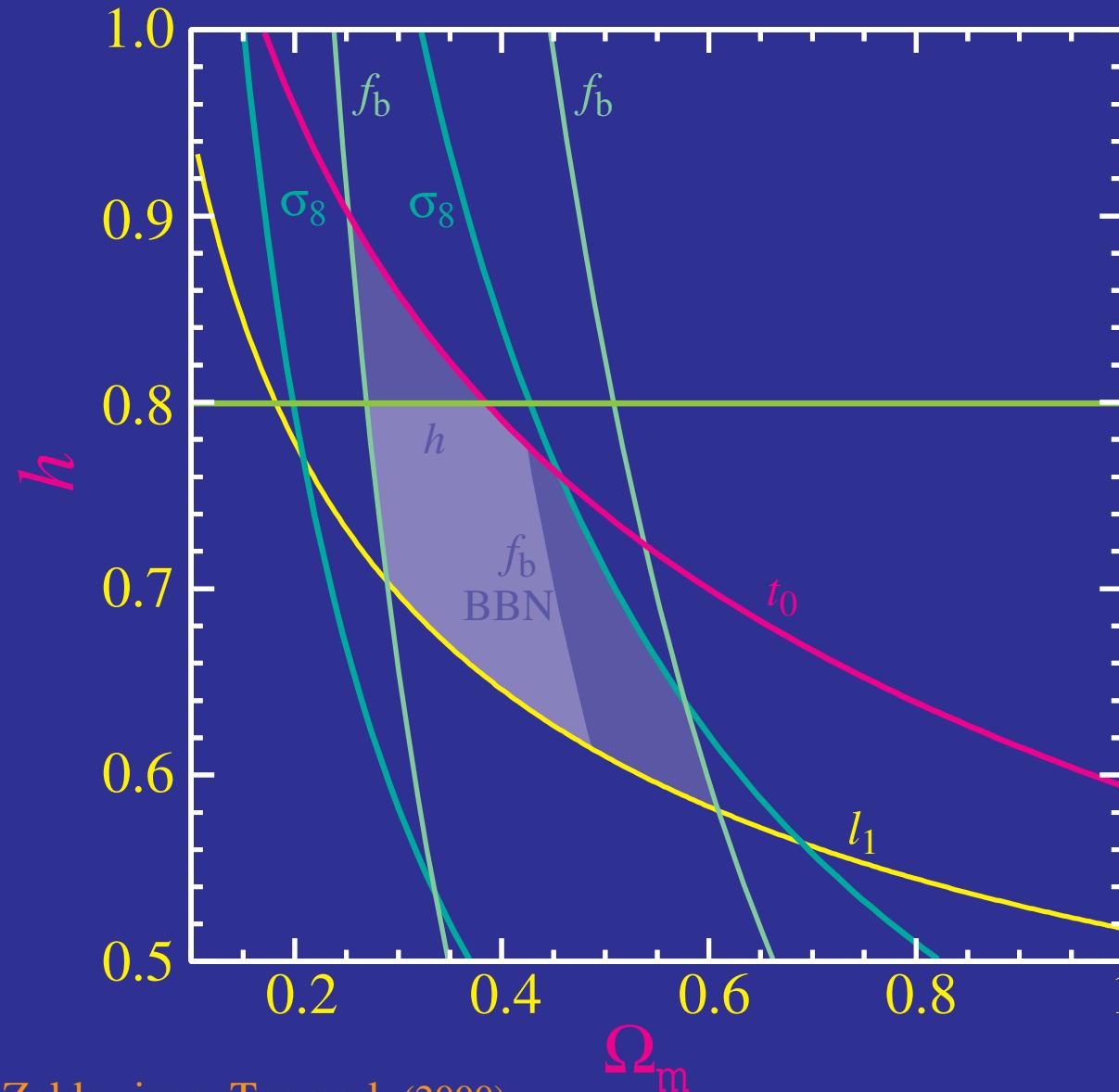
Age and Dark Energy

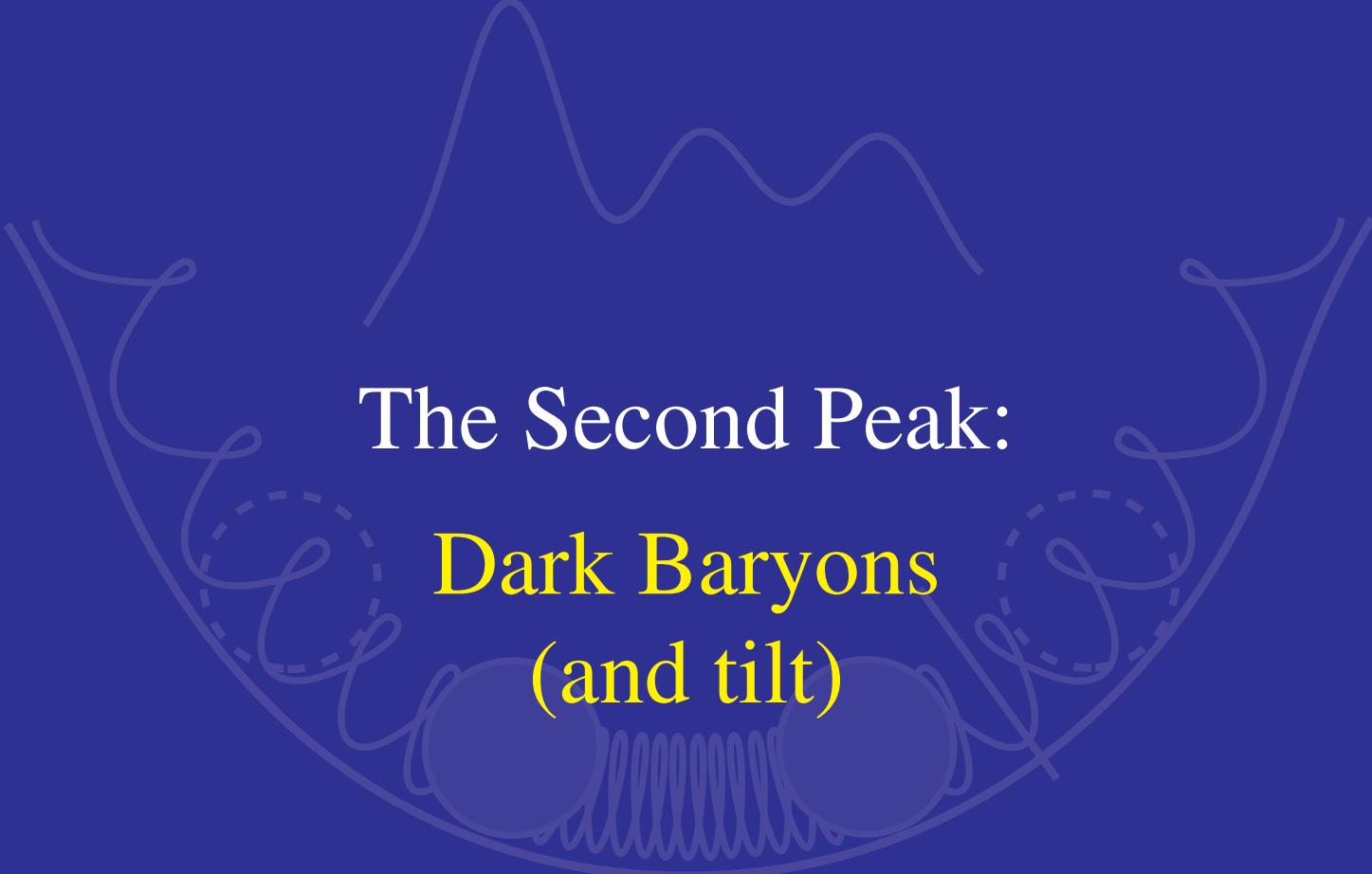
- Flat solutions involve decreasing age of universe through h , Ω_m or dark energy equation of state $w=p/\rho$ (<13–13.5Gyr)



Age and Dark Energy

- Region of consistency shrinking – headed to crisis?
- New physics? $w, m_v, \alpha...$

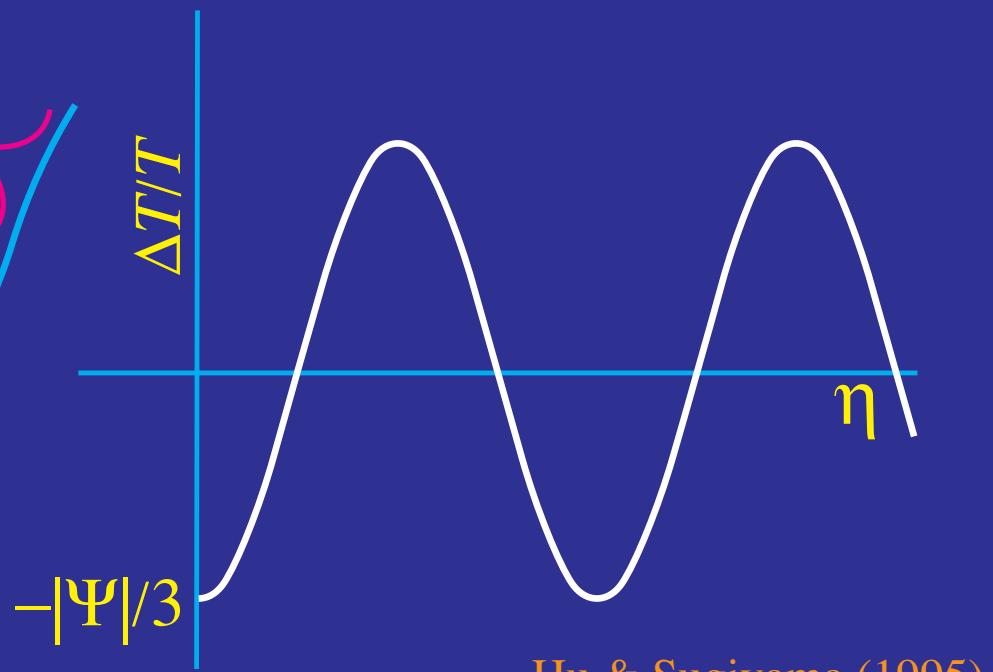
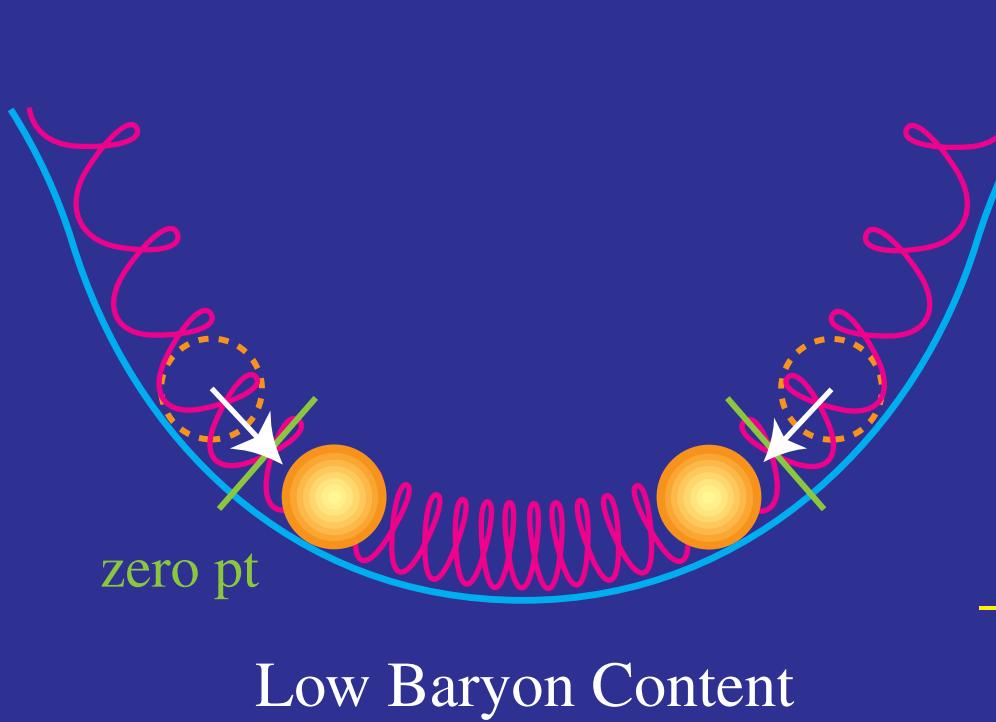




The Second Peak: Dark Baryons (and tilt)

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)

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** $m_{\text{eff}} = (1 + R)$

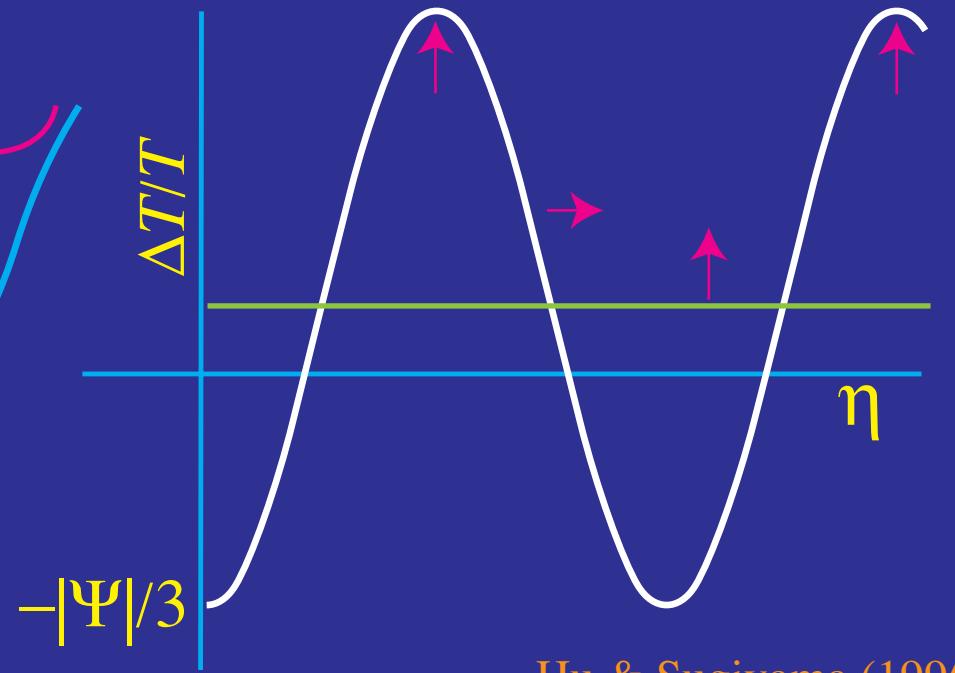
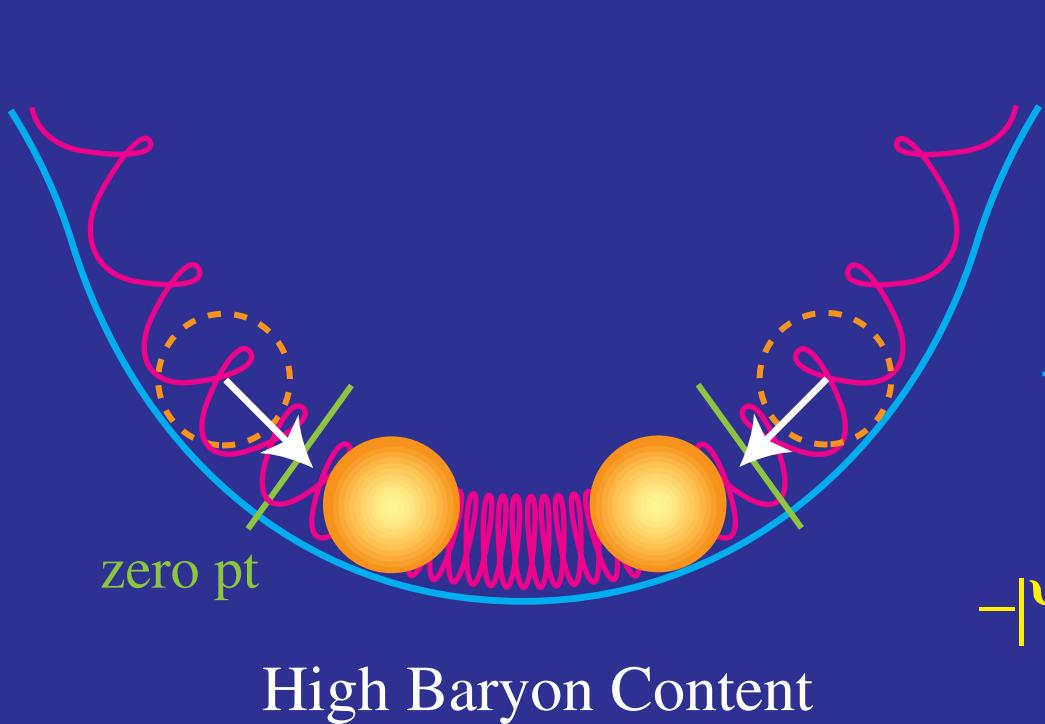
- Baryons drag photons into potential wells \rightarrow **zero point** \uparrow

- Amplitude \uparrow

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

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

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



Hu & Sugiyama (1995)

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** $m_{\text{eff}} = (1 + R)$

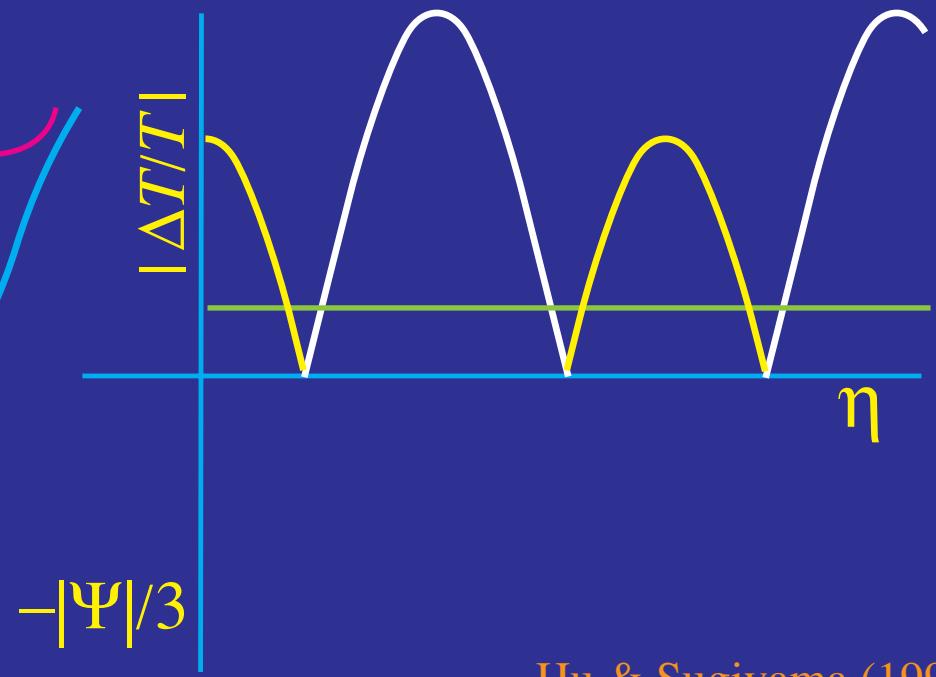
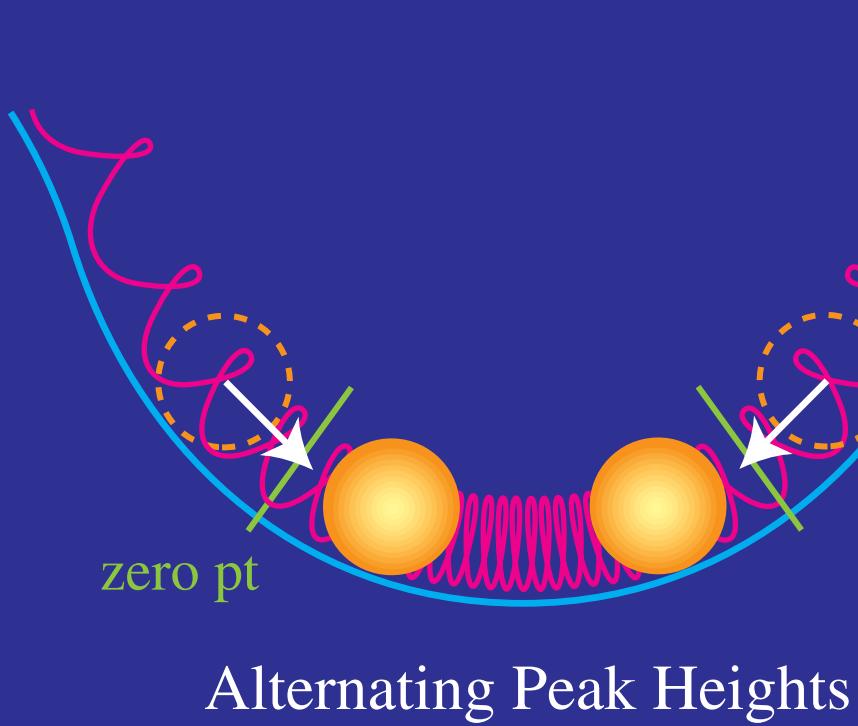
- Baryons drag photons into potential wells \rightarrow **zero point** \uparrow

- Amplitude \uparrow

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

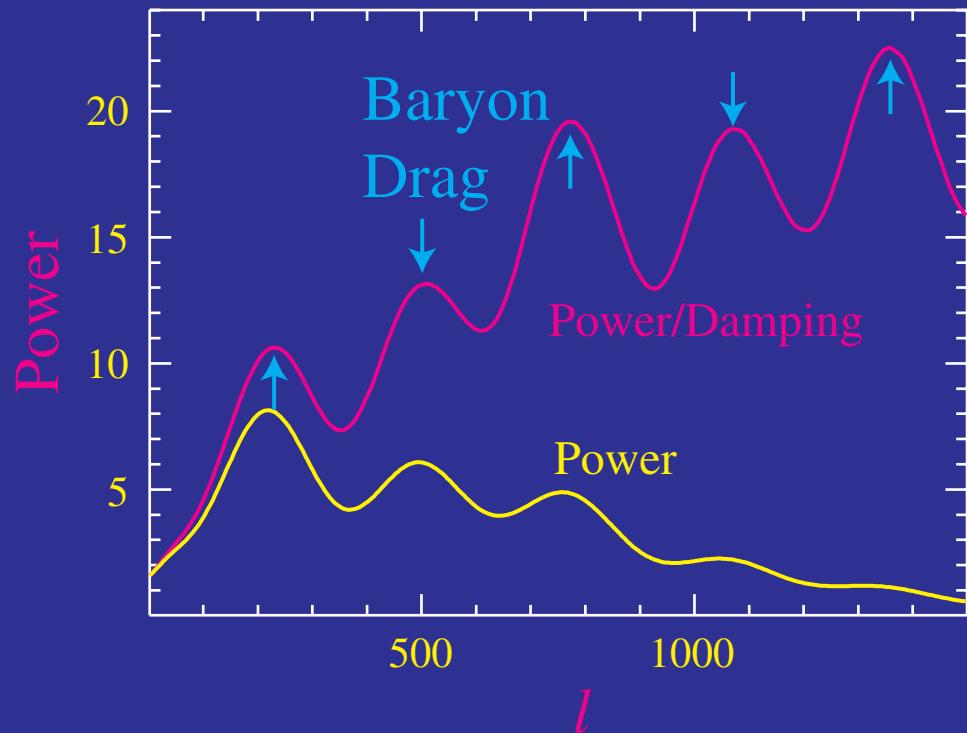
- Constant R , Ψ : $(1+R)\ddot{\Theta} + (k^2/3)\Theta = -(1+R)(k^2/3)\Psi$

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

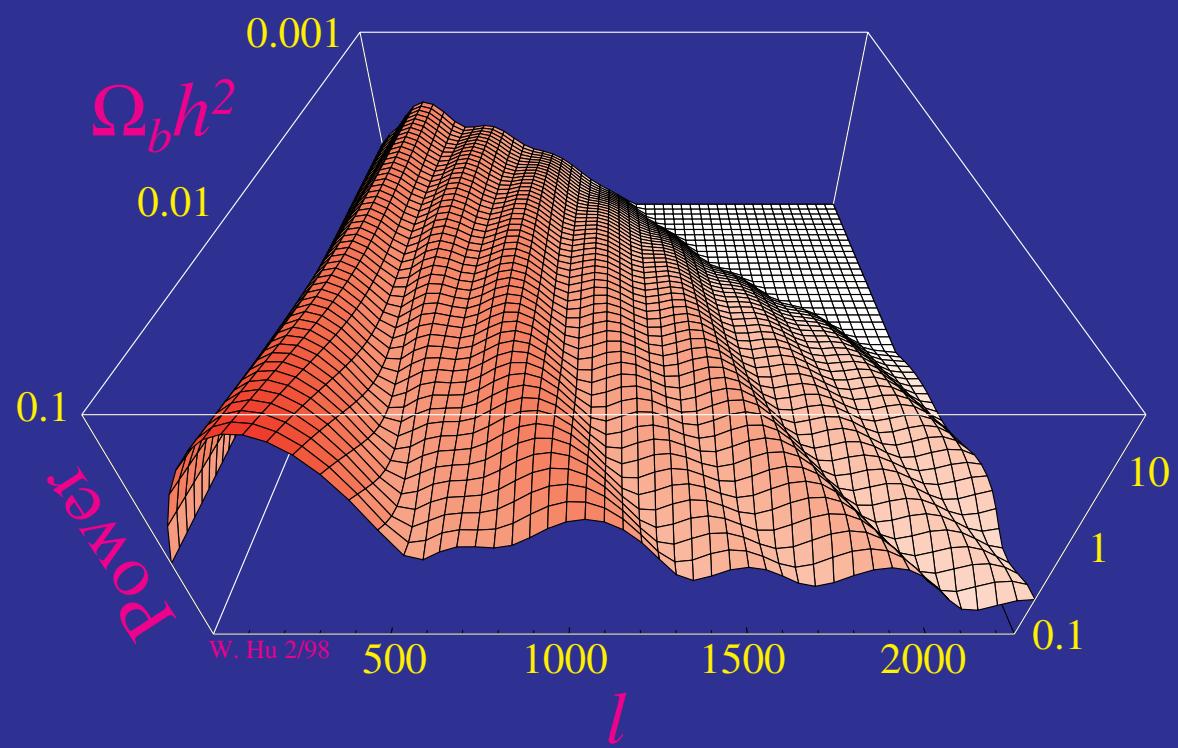


Hu & Sugiyama (1995)

Baryons in the CMB



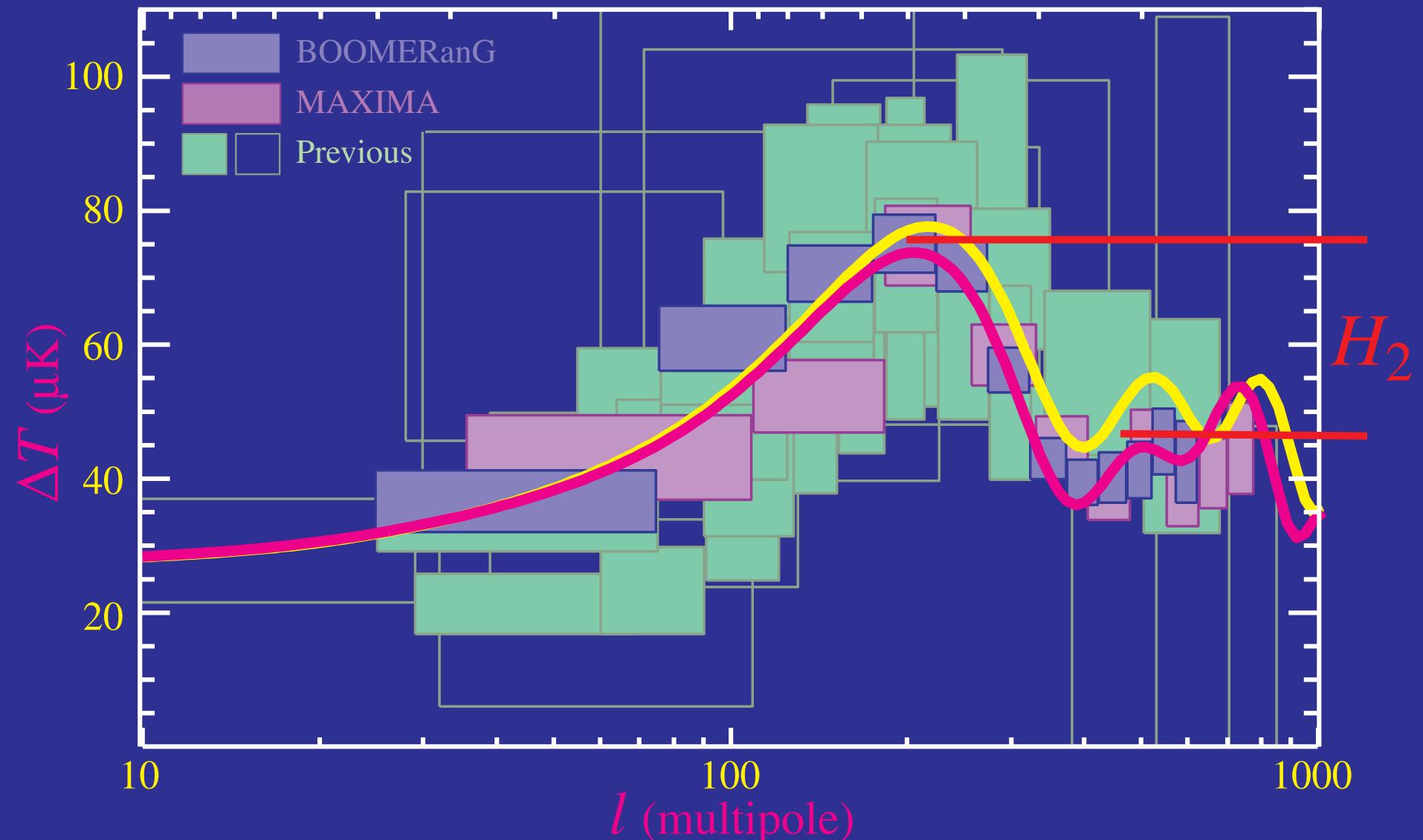
- Additional Effects
 - Time-varying potential
 - Dissipation/Fluid imperfections



- High odd peaks

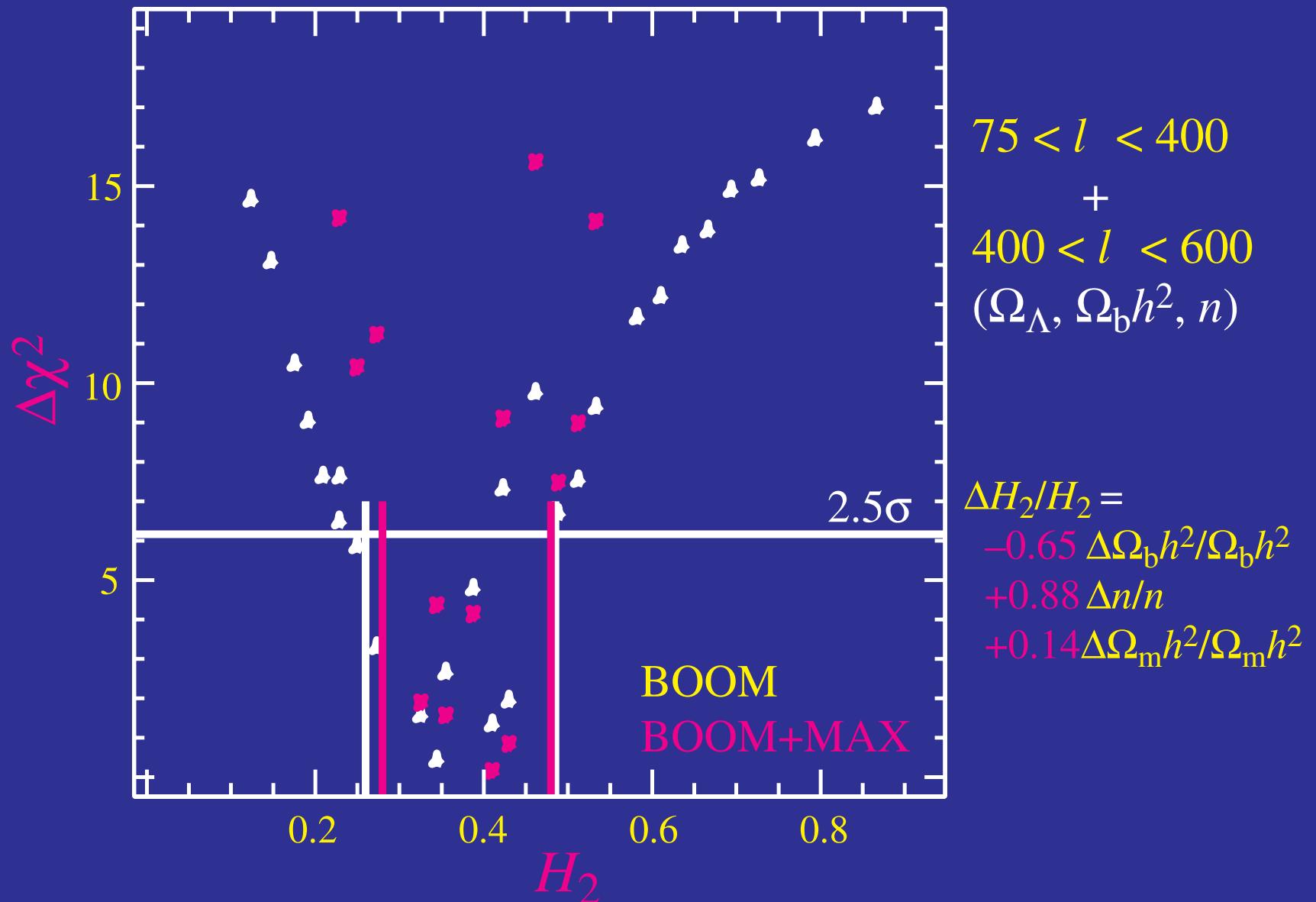
Height of the Second Peak

- BOOM and MAX both show a low power at $l_2 = 2.4 l_1$
- $H_2 = \text{power at 1st/2nd} = (\Delta T_{l_2}/\Delta T_{l_1})^2$



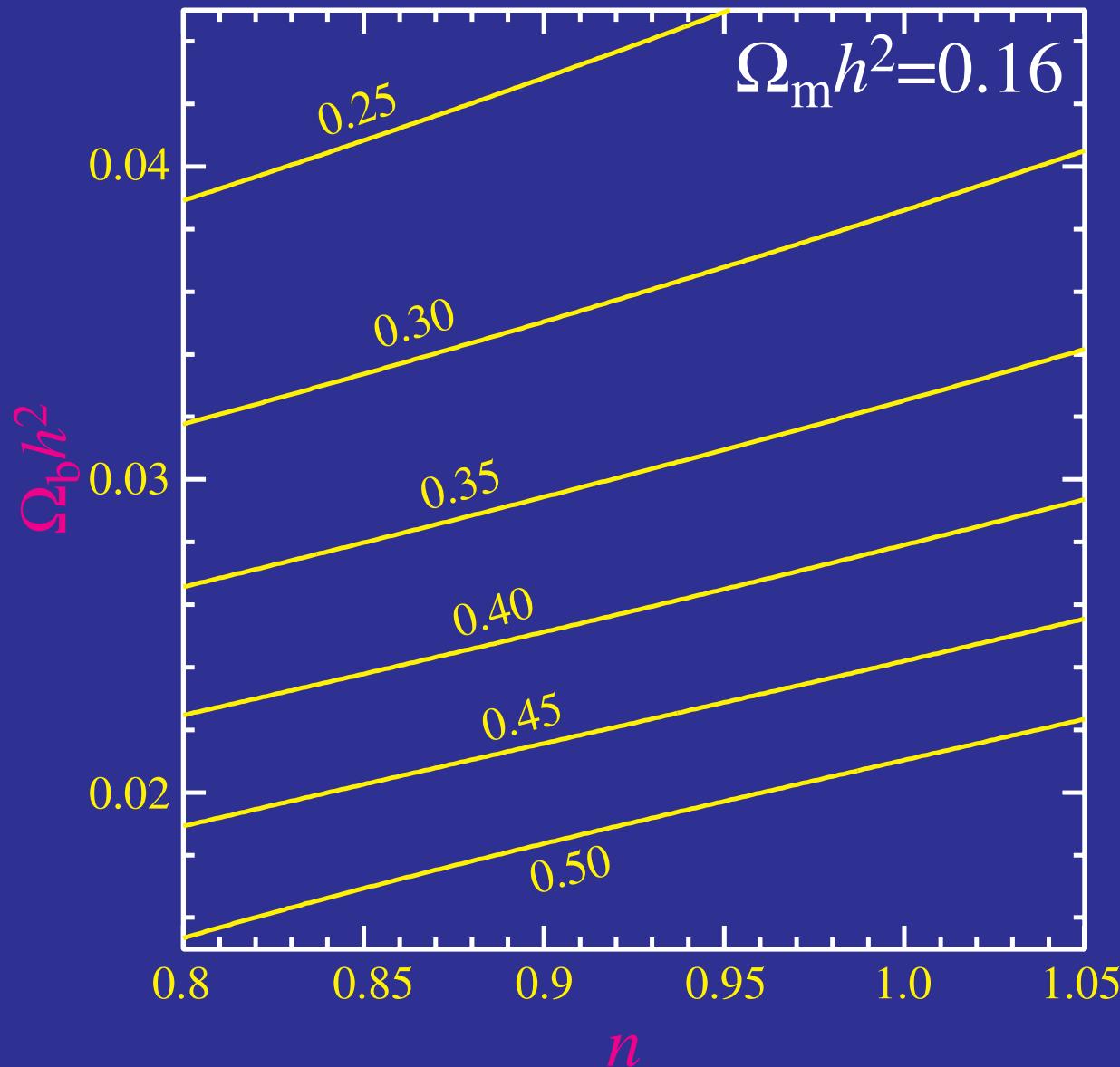
Height of the Second Peak

- BOOM : $H_2 = 0.37 \pm 0.044$ (1σ)
- BOOM+MAX: $H_2 = 0.38 \pm 0.04$ (1σ)



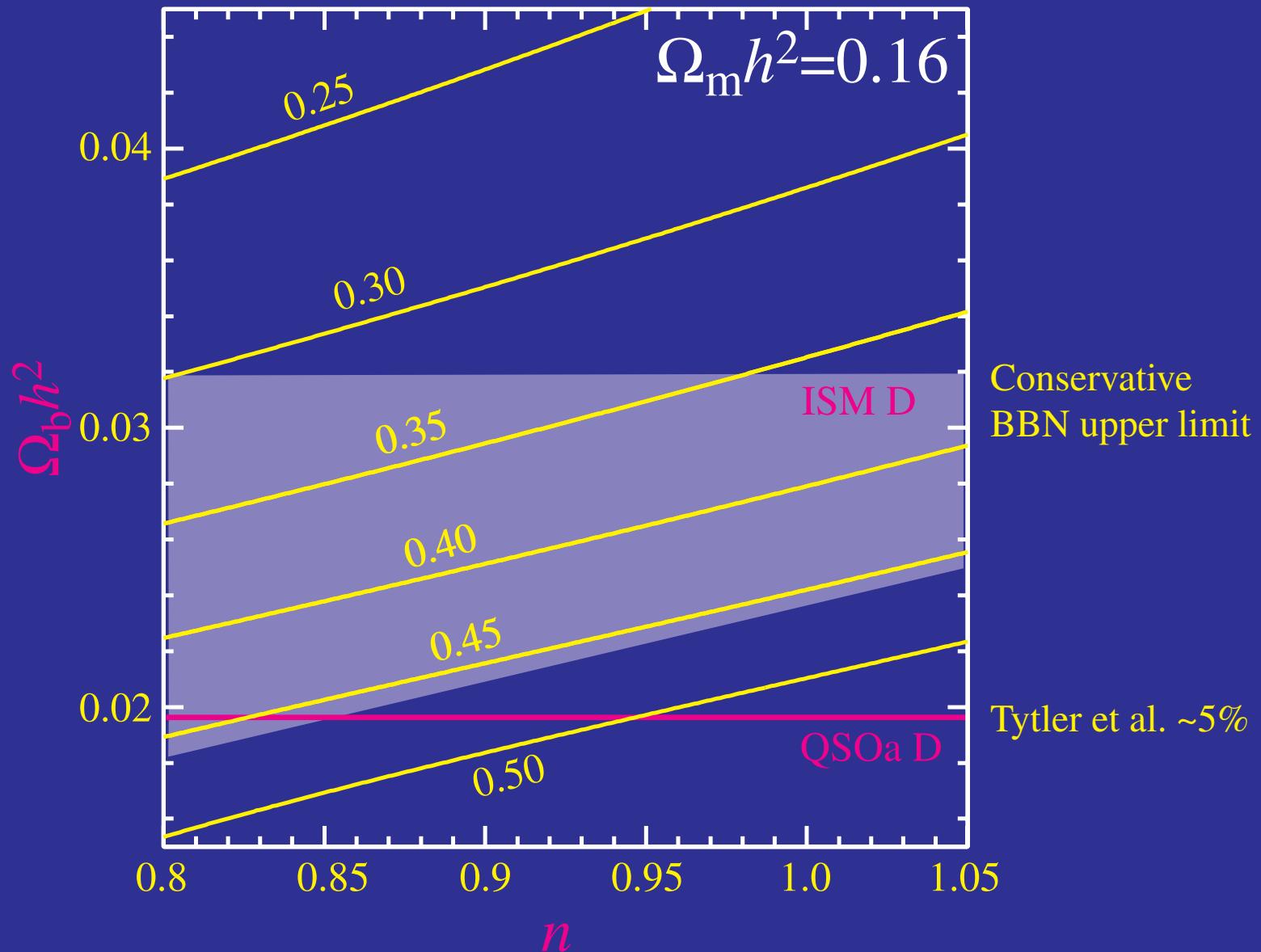
Height of the Second Peak

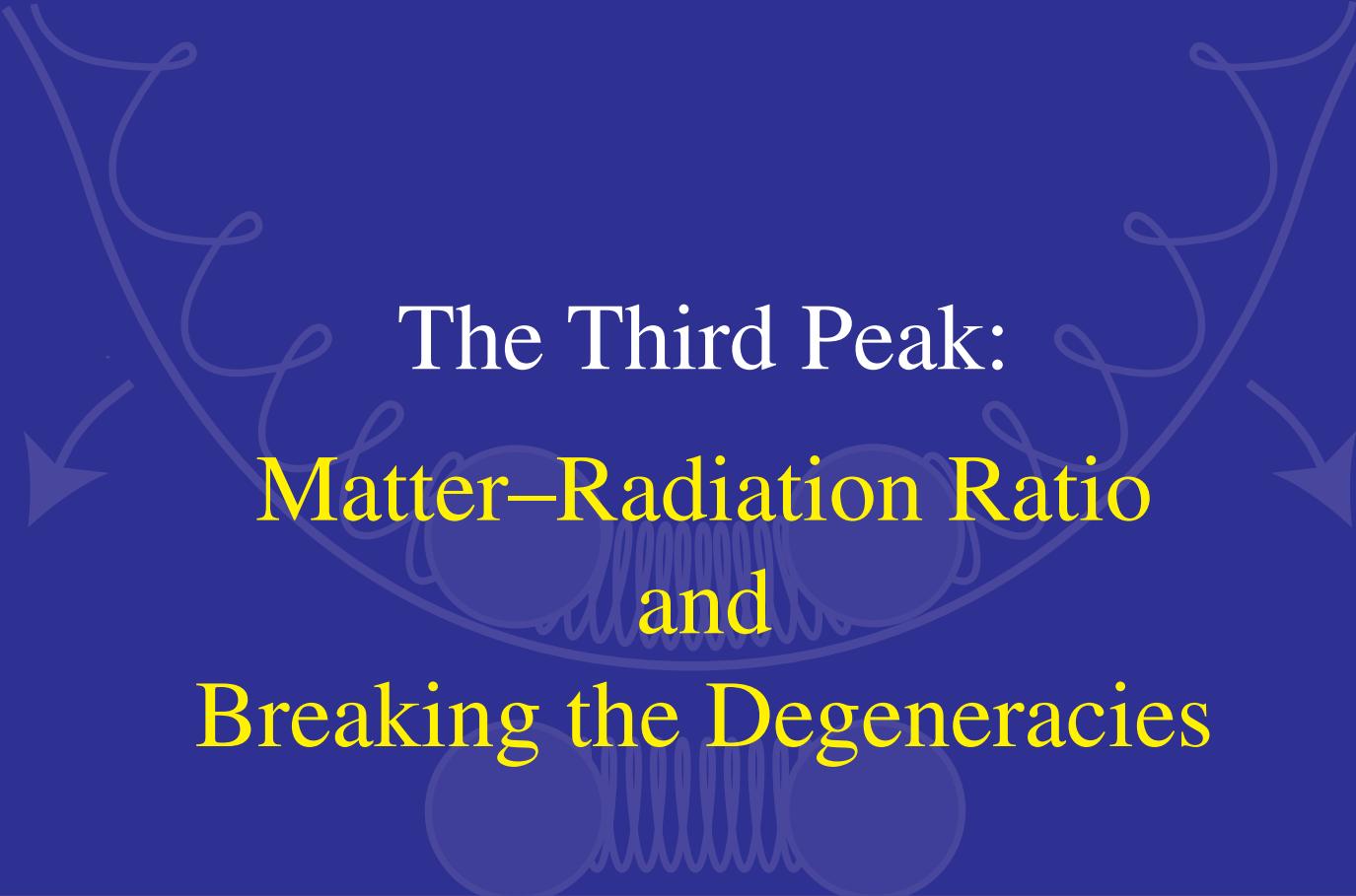
- Excludes fiducial LCDM ($n=1$, $\Omega_b h^2=0.02$, $H_2=0.51$) at $\sim 3.3\sigma$
- Requires $\Omega_b h^2 > 0.022n$ (if $\Omega_m h^2 > 0.16$, from l_1 , flat, $h < 0.8$)



Height of the Second Peak

- Excludes fiducial LCDM ($n=1$, $\Omega_b h^2=0.02$, $H_2=0.51$) at $\sim 3.3\sigma$
- Requires $\Omega_b h^2 > 0.022n$ (if $\Omega_m h^2 > 0.16$, from l_1 , flat, $h < 0.8$)

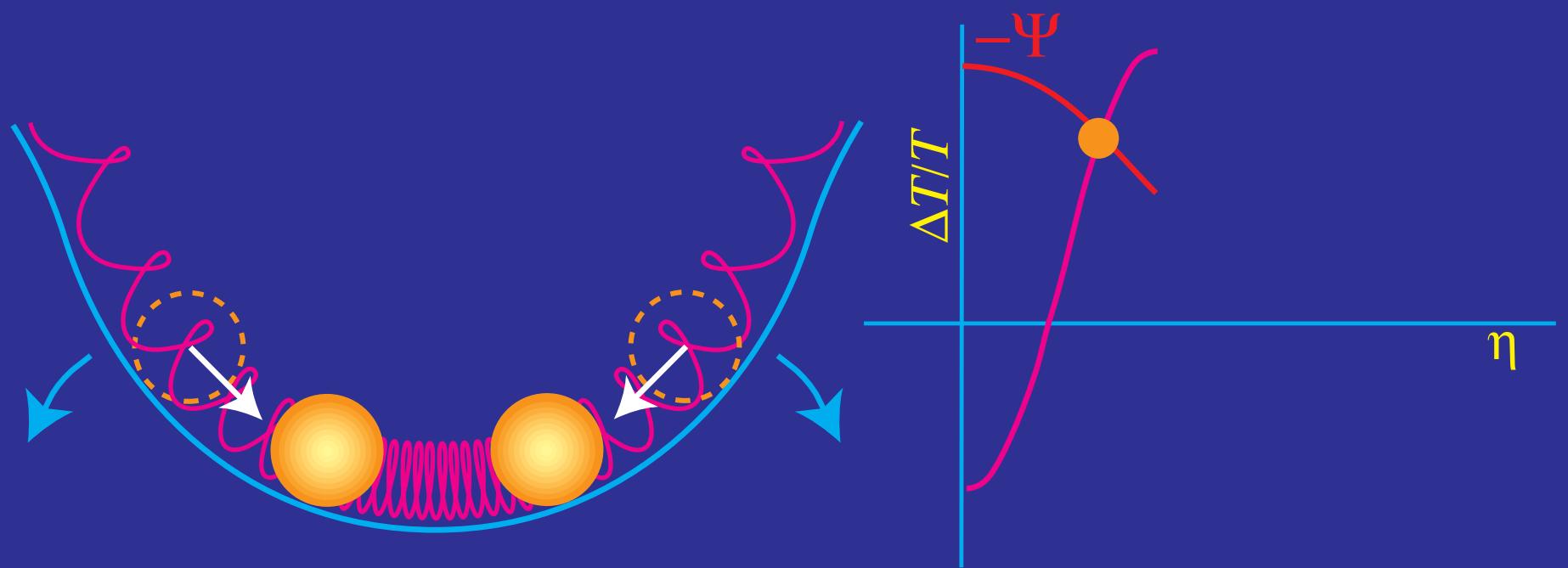




The Third Peak: Matter–Radiation Ratio and Breaking the Degeneracies

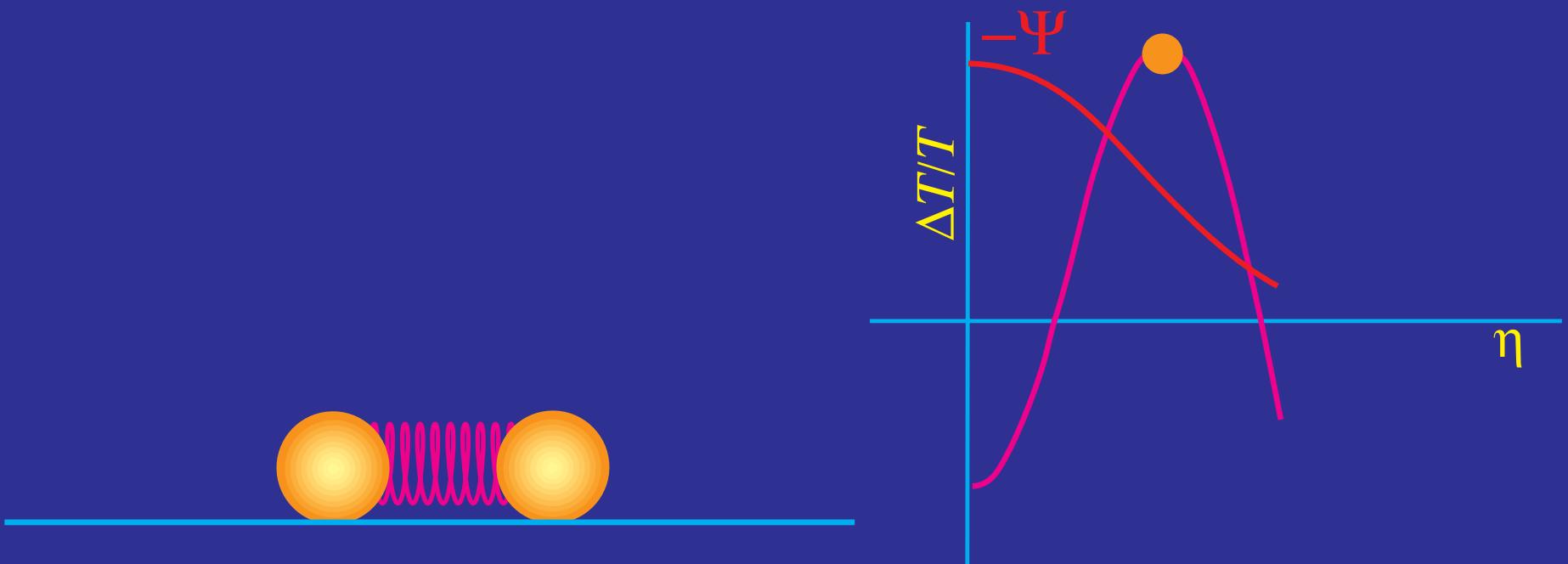
Driving Effects and Matter/Radiation

- 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 Ψ decays with expansion



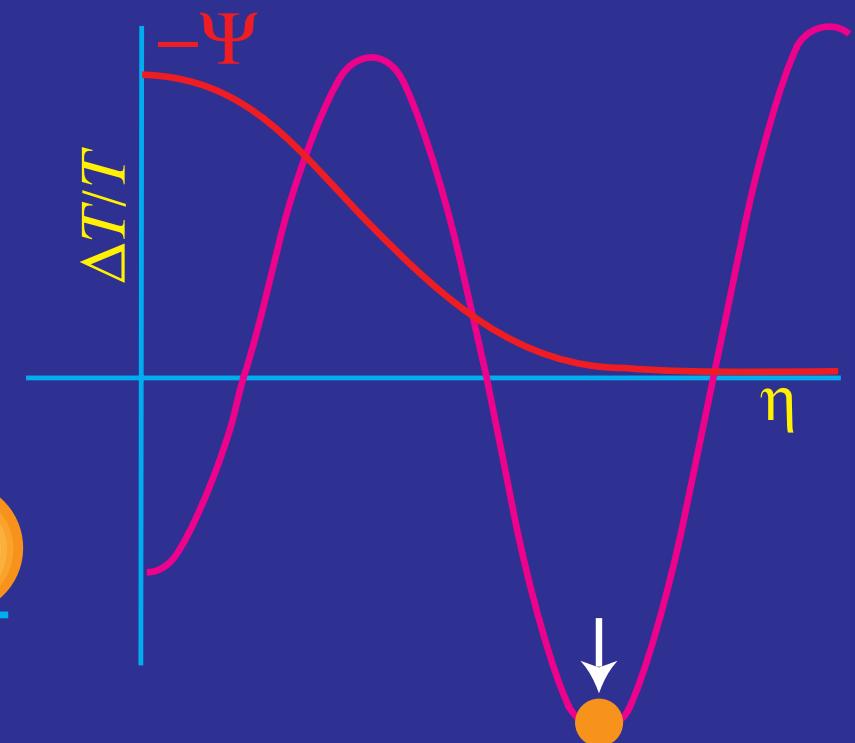
Driving Effects and Matter/Radiation

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

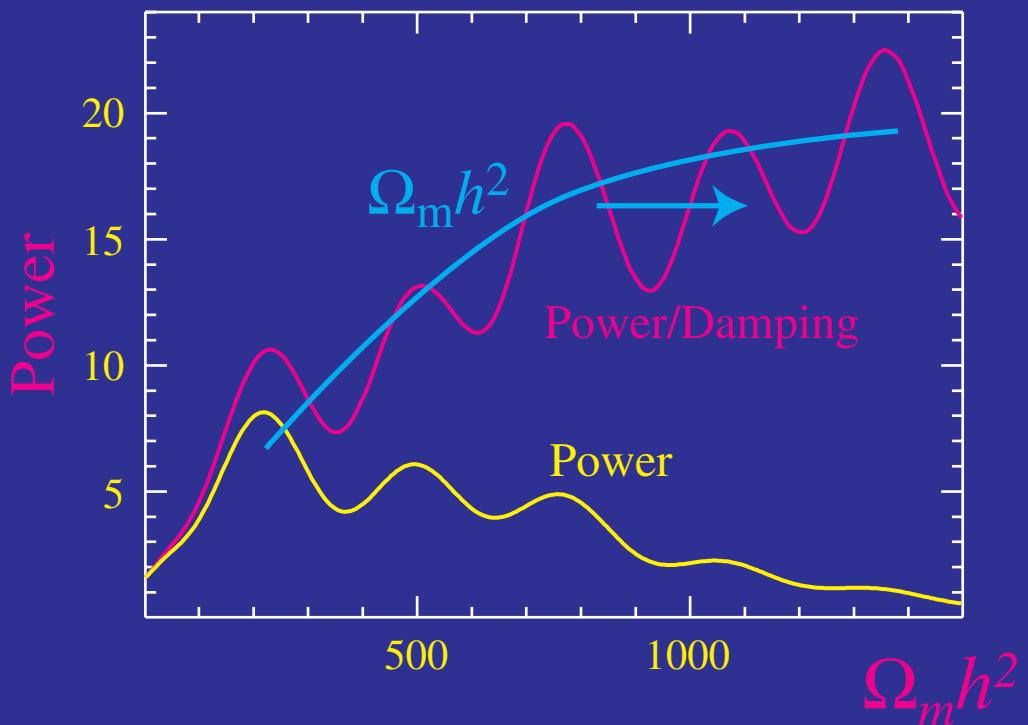


Driving Effects and Matter/Radiation

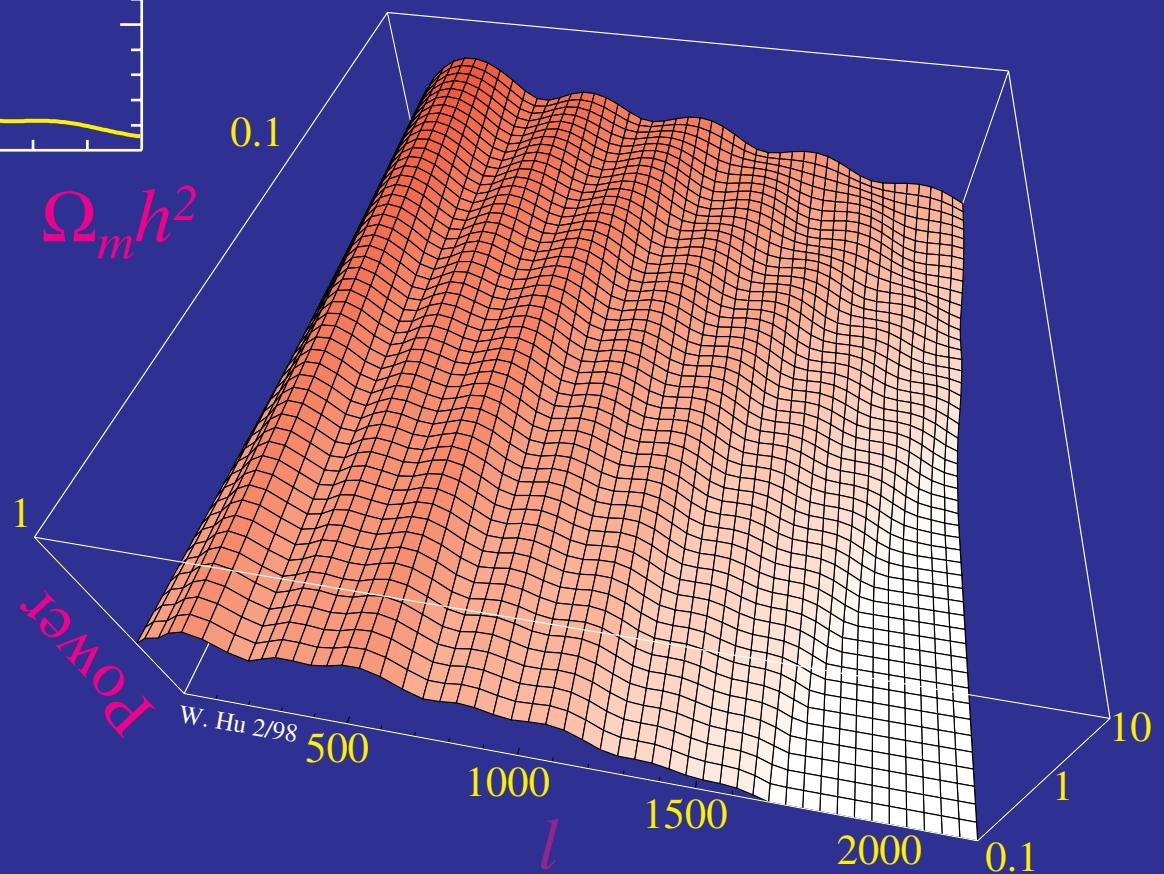
- Potential perturbation: $k^2\Psi = -4\pi Ga^2\delta\rho$ generated by radiation
- Radiation \rightarrow Potential: inside sound horizon $\delta\rho/\rho$ pressure supported $\delta\rho$ hence Ψ decays with expansion
- Potential \rightarrow Radiation: Ψ -decay timed to drive oscillation
 $-2\Psi + (1/3)\Psi = -(5/3)\Psi \rightarrow 5x$ boost
- Feedback stops at matter domination



Matter Density in the CMB



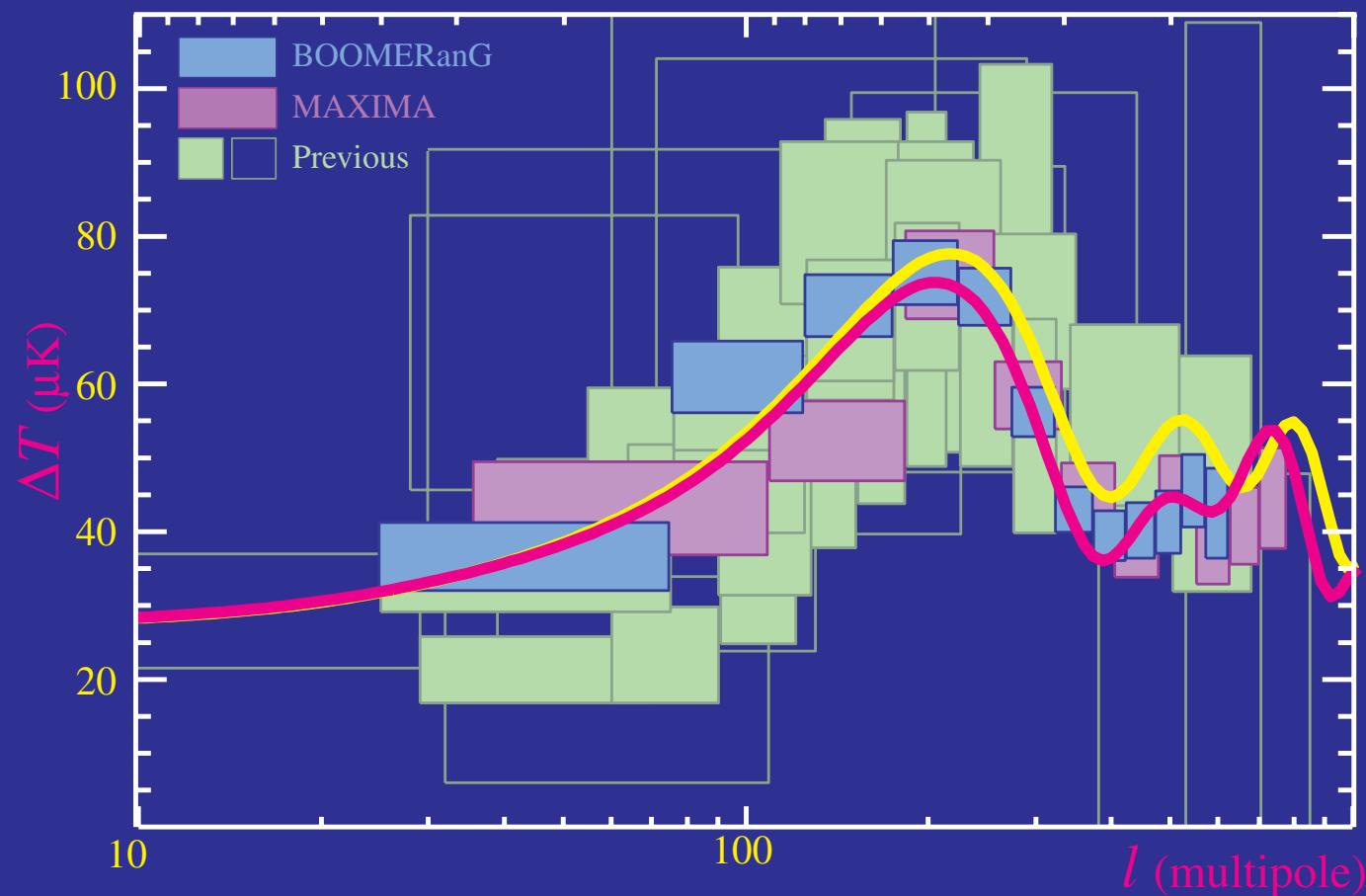
- Amplitude ramp across matter–radiation equality
- Radiation density fixed by CMB temperature & thermal history



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

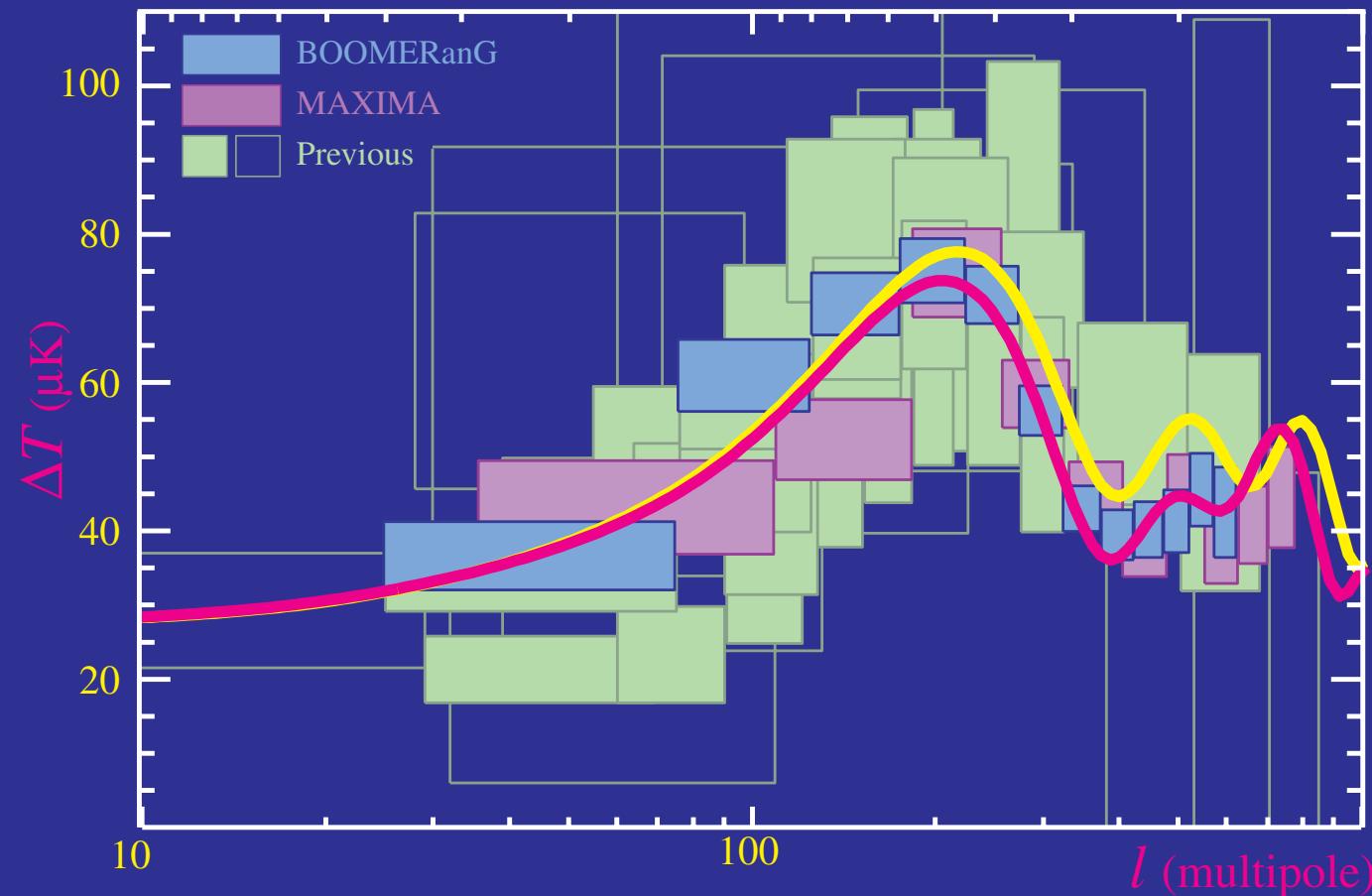
Height of the Third Peak

- MAX at $600 < l < 800$ constrains third peak
- $H_3 = 3\text{rd} / 1\text{st}$ peak heights in power $(\Delta T_{l_3}/\Delta T_{l_1})^2$
- $H_3 < 0.6$ at 2σ implies $\Omega_m h^2 < 0.45$ (but > 0.16 , l_1 if flat)



Height of the First Peak

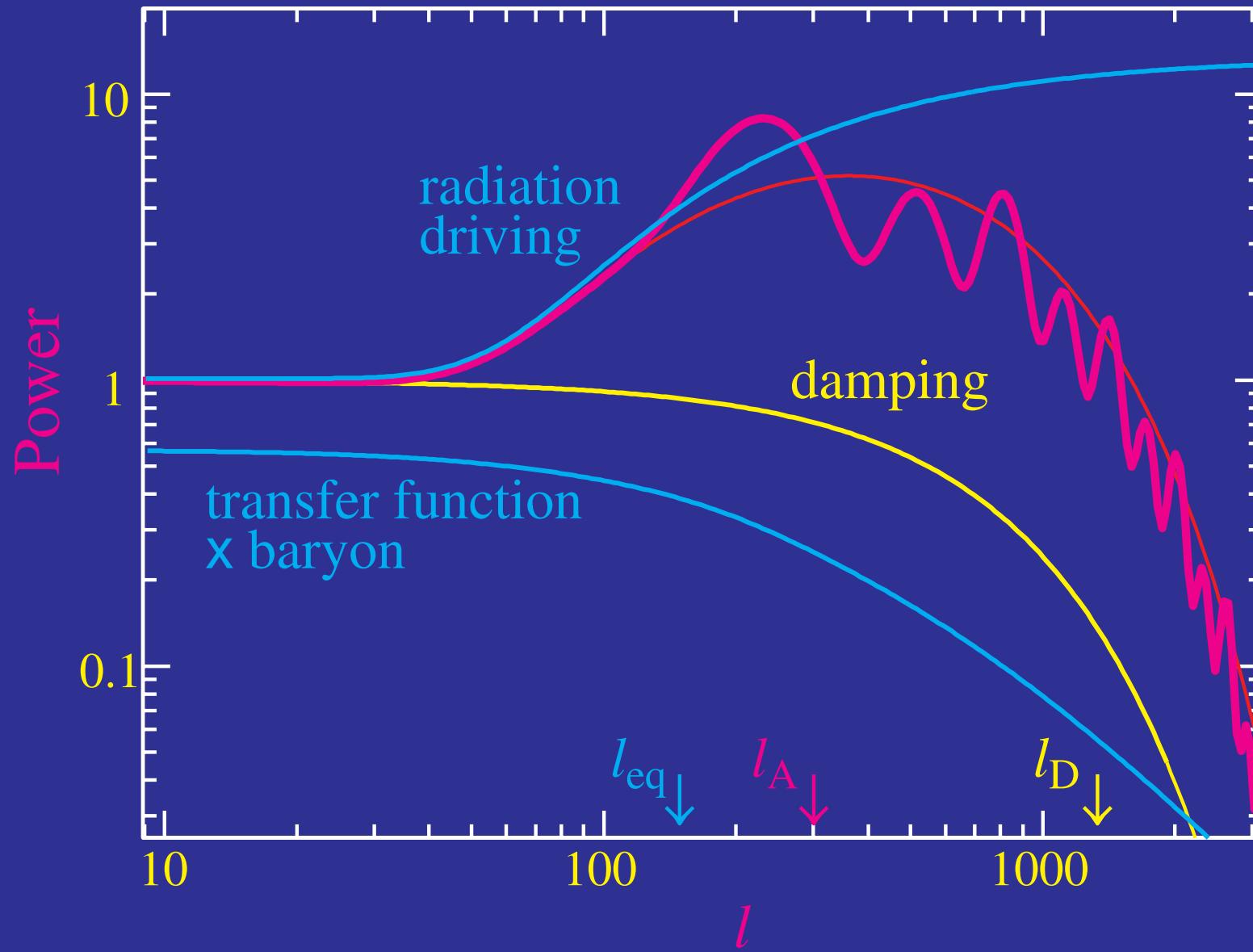
- Height compared with COBE $l=10$: 7.6 ± 1.4 (cosmic var. & calibration)
- With $\Omega_m h^2$ and $\Omega_b h^2$ constraining peak morphology, $H_1 > 4.8$ implies $n > 0.85$ (near scale-invariant initial fluctuations)



- Limit on $H_2 + (n > 0.85) \rightarrow \Omega_b h^2 > 0.019$ (at least BBN)

Acoustic Phenomenology

- Baryons: baryon drag, dissipation – alternating peaks, exponential fall
- Matter-Radiation: potential decay – radiation driving, drag reduction



Summary

- We have entered a new era of precision cosmology
- First peak in the CMB power spectrum is due to acoustic waves at $z \sim 1000$ based on the precise shape measurement
- Consistent with simple inflationary models (scale-invariant superhorizon density perturbations, $n > 0.85$)
- First peak consistent with a flat universe but may indicate a young age (prefers $\sim 10\text{-}11$ Gyrs, requires $< 13\text{-}14$ Gyrs from $l_1 < 218$ [95%CL])
possible causes: high Hubble constant, Ω_m , or dark energy p/ρ)
- Requires dark baryons at least comparable to big-bang nucleosynthesis (prefers 25-50% more: low second peak $H_2 < 0.46$ [95%CL])
- Limits dark matter: lack of steep rise to third peak $\Omega_m h^2 < 0.47$)
- Still need to resolve the secondary peaks (stronger test of inflation)!
- Parameter degeneracies resolved with 3 peaks

Index

- COBE
- Current Power Spectrum
- Thermal History
- Acoustic Oscillations
- Acoustic Peaks
- Doppler Peaks (not)
- Curvature
- Peak Location and Age
- Dark Baryons
- Baryon Drag
- Dissipation
- Height of Second Peak
- Matter/Radiation
- Third Peak ?
- Inflation
- Polarization

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

Outtakes