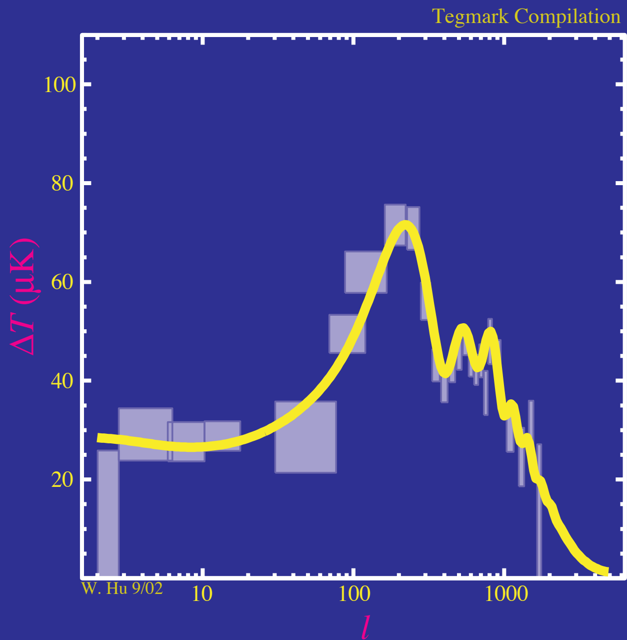
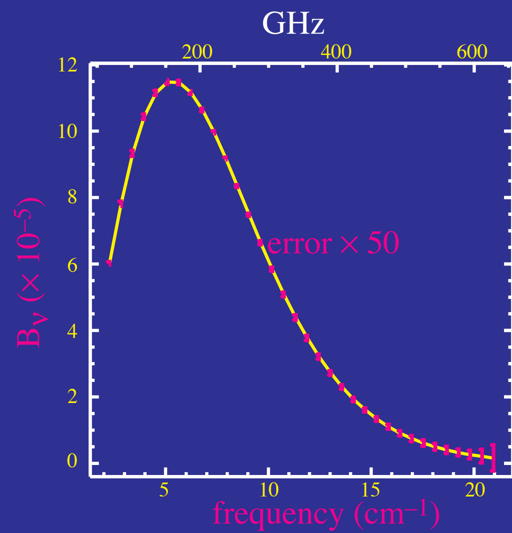
# CMB Observables

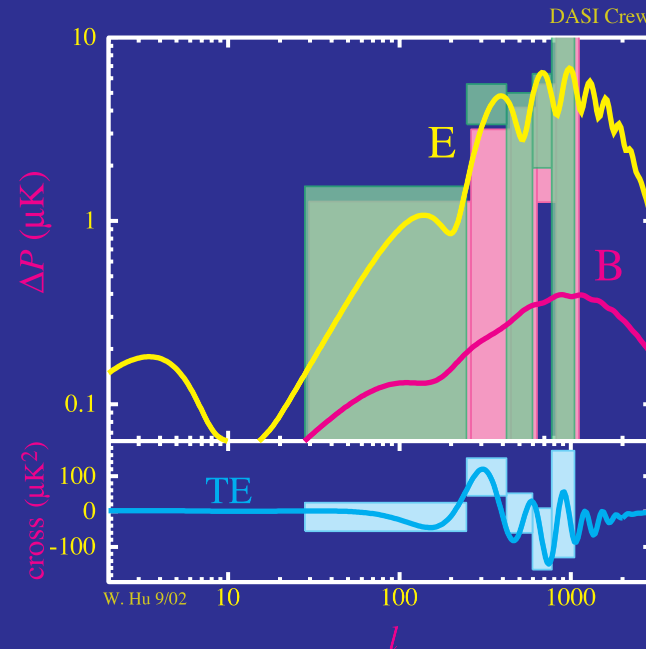
anisotropy




spectrum

polarization




and their Cosmological Implications

*Wayne Hu*

Maryland, October 2002

# CMB Milestones

| | | |
|---|---|---|
| • Blackbody spectrum | COBE FIRAS | '92 |
| • Large-scale anisotropy | COBE DMR | '92 |
| • Degree-scale anisotropy | many | '93-'99 |
| • First acoustic peak | Toco, Boom, Maxima | '99-'00 |
| • Secondary acoustic peak(s) | DASI, Boom | '01 |
| • Damping tail | CBI | '02 |
| • Polarization | DASI | '02 |
| • Secondary anisotropy? Spectrum? | CBI | '02 |

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http://background.uchicago.edu

("Presentations" in PDF)

# Anisotropy Power Spectrum

# Sound Physics

# Photon-Baryon Plasma

- Before $z \sim 1000$ when the CMB had $T > 3000$K, hydrogen ionized
- Free electrons act as "glue" between photons and baryons by Compton scattering and Coulomb interactions
- Nearly perfect fluid

# Acoustic Basics

- Continuity Equation: (number conservation)

$$\dot{\Theta} = -\frac{1}{3} k v_\gamma$$

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- Combine these to form the simple harmonic oscillator equation

$$\ddot{\Theta} + c_s^2 k^2 \Theta = -\frac{k^2}{3}\Psi$$

where $c_s^2 \equiv \dot{p}/\dot{\rho}$ is the sound speed squared

# Harmonic Peaks

- Adiabatic (Curvature) Mode Solution

$$[\Theta + \Psi](\eta) = [\Theta + \Psi](0)\ \cos(ks)$$

where the sound horizon $s \equiv \int c_s d\eta$ and $\Theta + \Psi$ is also the observed temperature fluctuation after gravitational redshift

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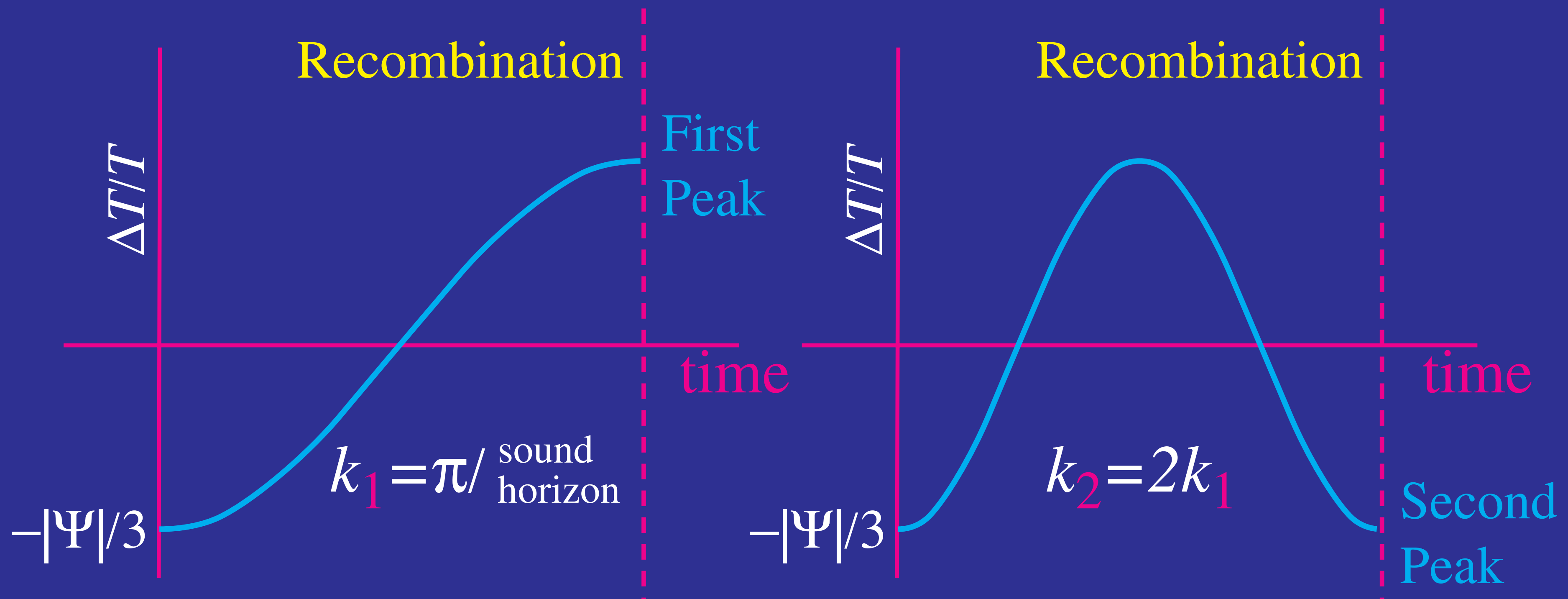
- Modes caught in the extrema of their oscillation will have enhanced fluctuations

$$k_n s_* = n\pi$$

yielding a fundamental scale or frequency, related to the inverse sound horizon

# Extrema=Peaks

- First peak = mode that just compresses
- Second peak = mode that compresses then rarefies
- Third peak = mode that compresses then rarefies then compresses



# Peak Location

- Fundmental physical scale, the distance sound travels, becomes an angular scale by simple projection according to the angular diameter distance $D_A$

$$
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\theta_A &= \lambda_A / D_A \\
\ell_A &= k_A D_A
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- In a flat universe, the distance is simply $D_A = D \equiv \eta_0 - \eta_* \approx \eta_0$, the horizon distance, and $k_A = \pi/s_* = \sqrt{3}\pi/\eta_*$ so

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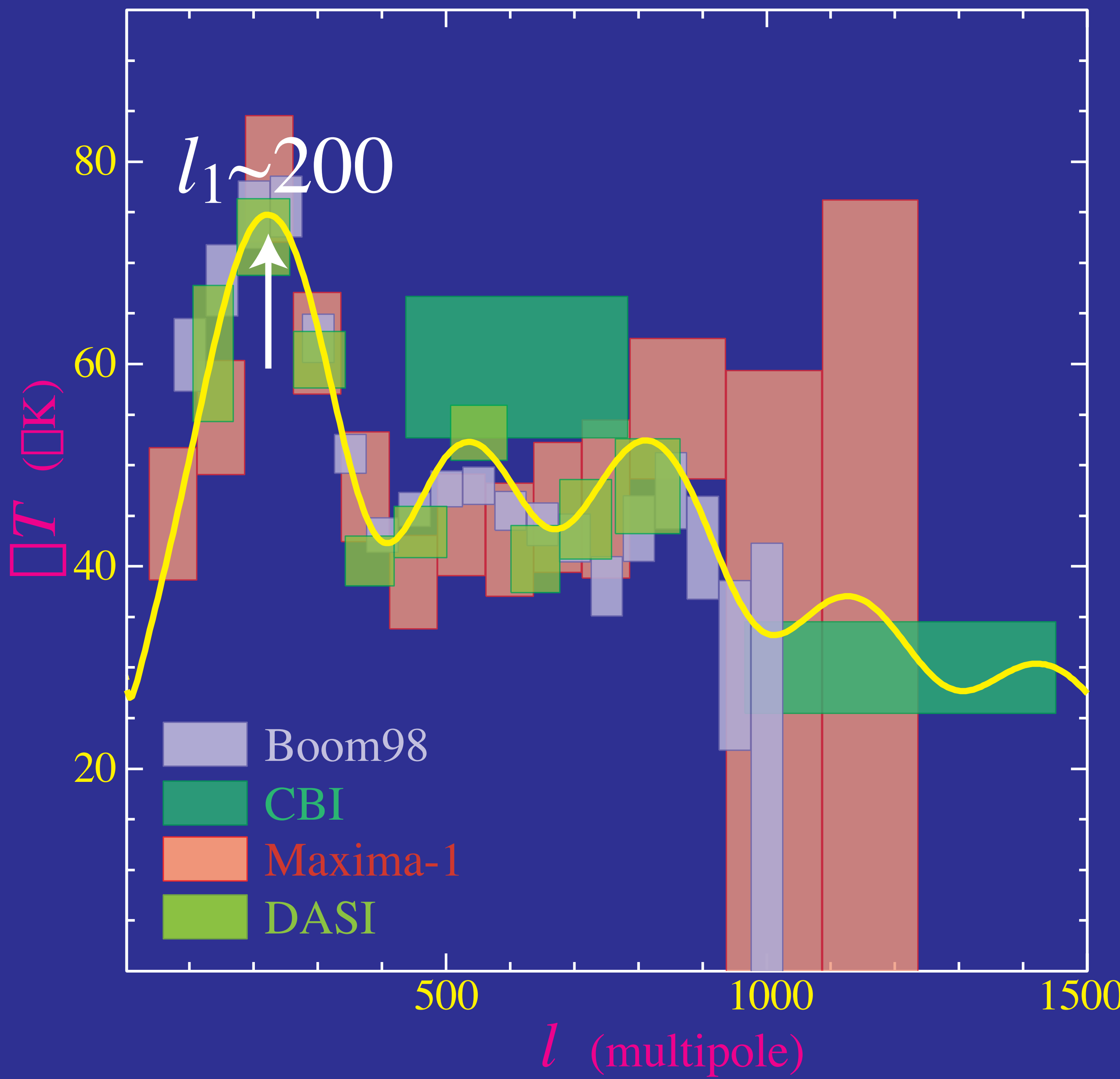
- In a matter-dominated universe $\eta \propto a^{1/2}$ so $\theta_A \approx 1/30 \approx 2^\circ$ or

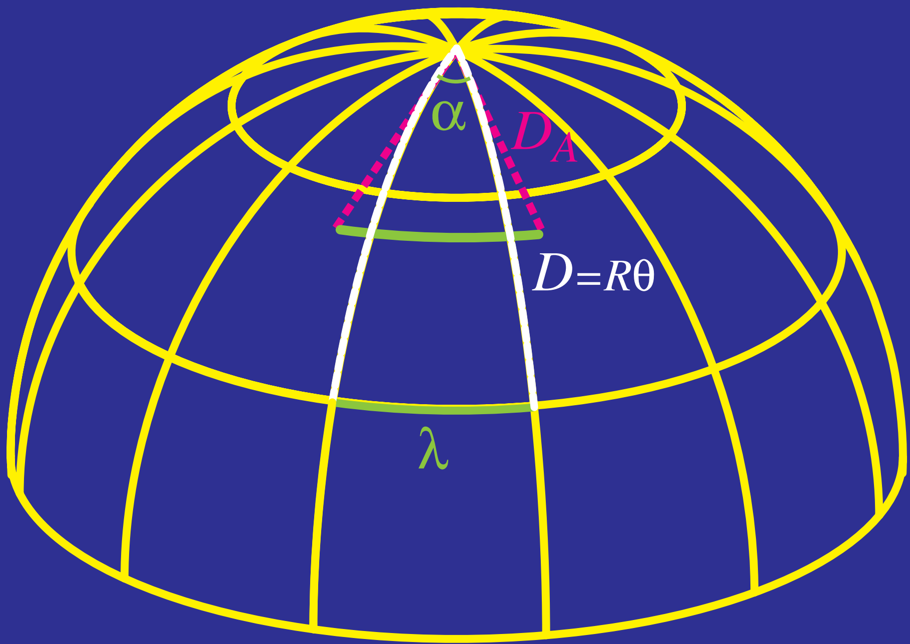
$$\ell_A \approx 200$$

# Angular Diameter Distance Test



# Curvature

- In a curved universe, the apparent or angular diameter distance is no longer the conformal distance $D_{\mathrm{A}} = R \sin(D/R) \neq D$




- Comoving objects in a closed universe are further than they appear! gravitational lensing of the background...

# Curvature in the Power Spectrum

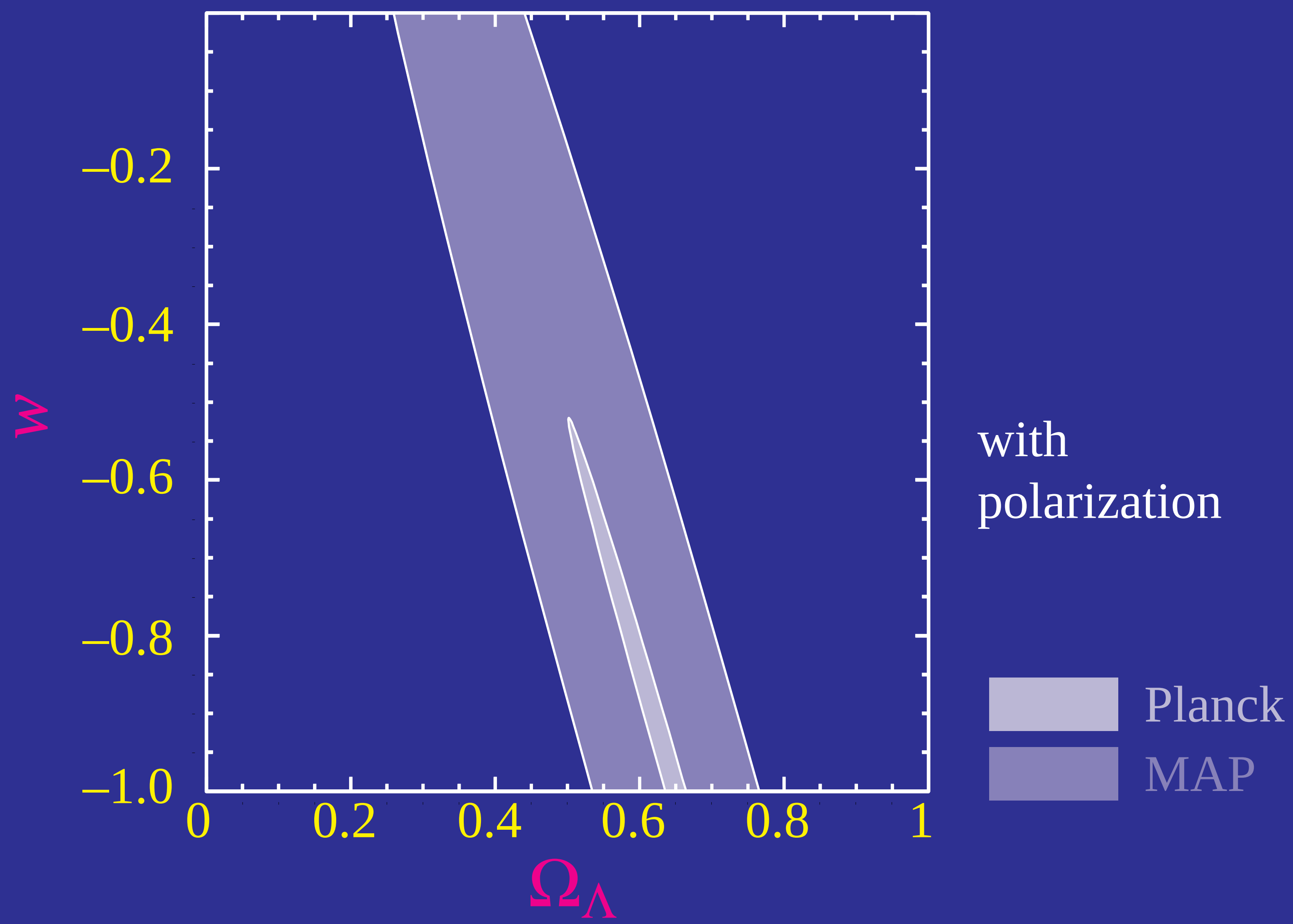
- Flat = critical density = missing dark energy
- How flat (or how much d.e.) depends on matter-radiation ratio

# Dark Energy in the Power Spectrum

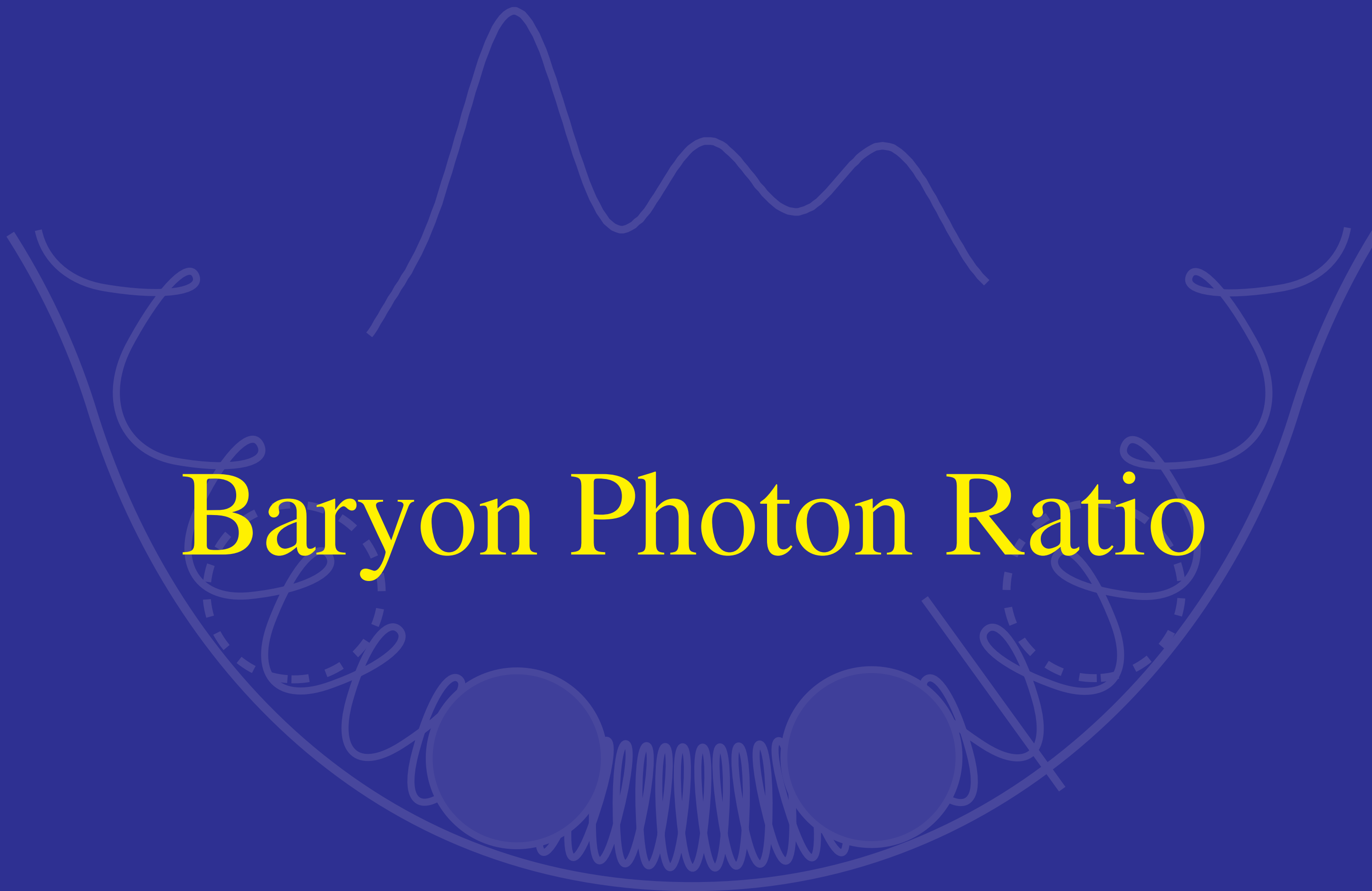
- Fundamental observable is sound horizon / ang. distance

# Importance of Higher Peaks & Polarization

- Width: matter-radiation ratio, extent polarization and $H_0$



# Baryon Photon Ratio



# Baryon Loading

- Baryons add extra mass to the photon-baryon fluid
- Controlling parameter is the momentum density ratio:

$$R \equiv \frac{p_b + \rho_b}{p_\gamma + \rho_\gamma} \approx 30\Omega_b h^2 \left(\frac{a}{10^{-3}}\right)$$

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$$\begin{aligned} \dot{\Theta} &= -\frac{k}{3} v_{\gamma b} \\ \dot{v}_{\gamma b} &= -\frac{\dot{R}}{1+R} v_{\gamma b} + \frac{1}{1+R} k\Theta + k\Psi \end{aligned}$$

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- In the slowly varying $R$ limit

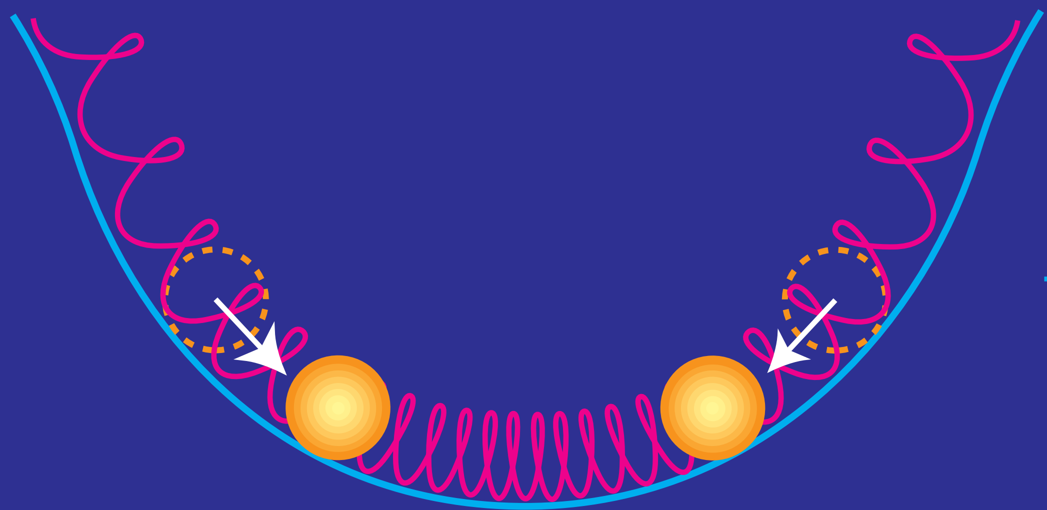
$$[\Theta + (1+R)\Psi](\eta) = [\Theta + (1+R)\Psi](0) \cos(ks)$$

# Baryon & Inertia

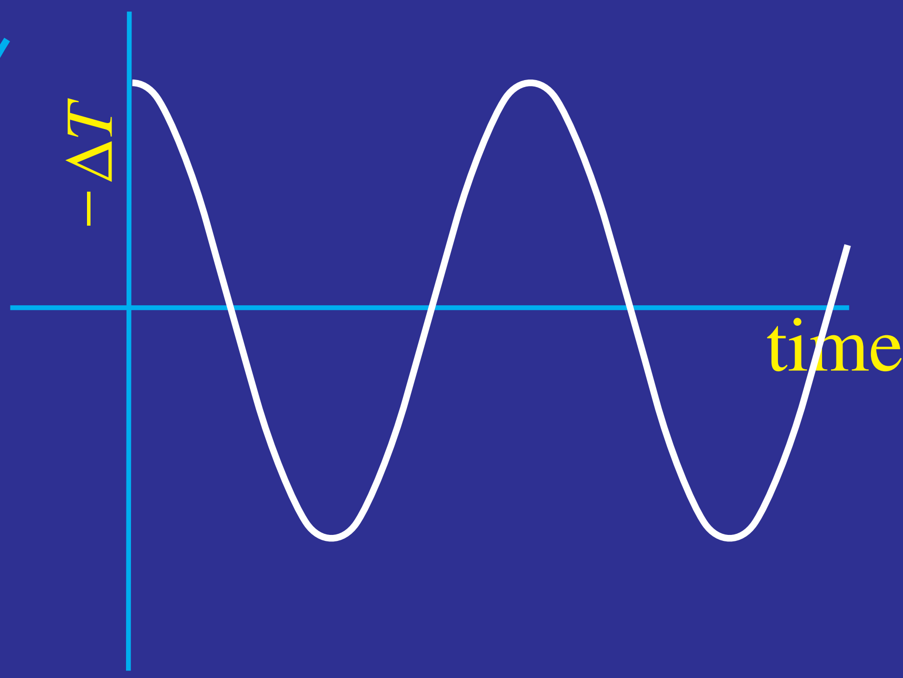
- Baryons add inertia to the fluid like mass on a spring

# Peak Modulation

- Low baryons: symmetric compressions and rarefactions



Low Baryons



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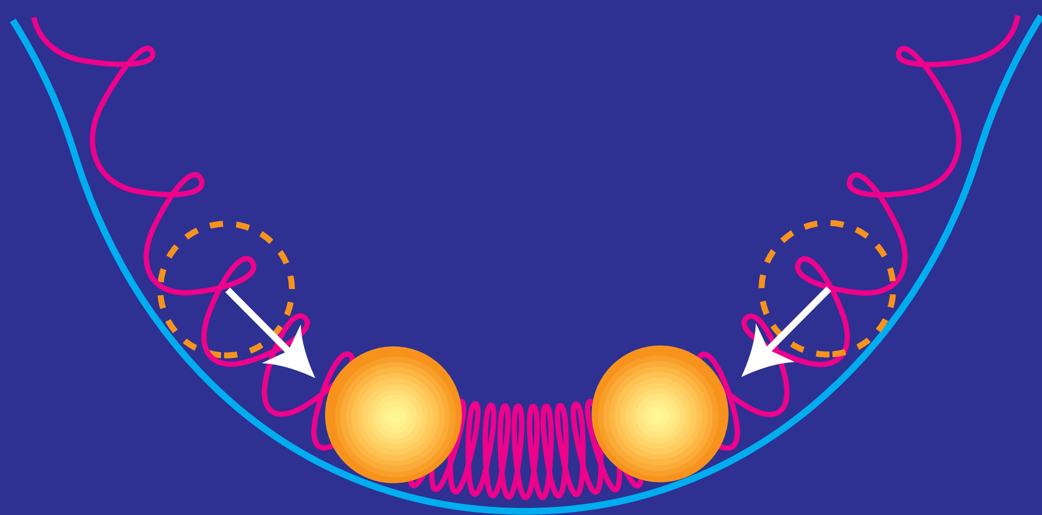

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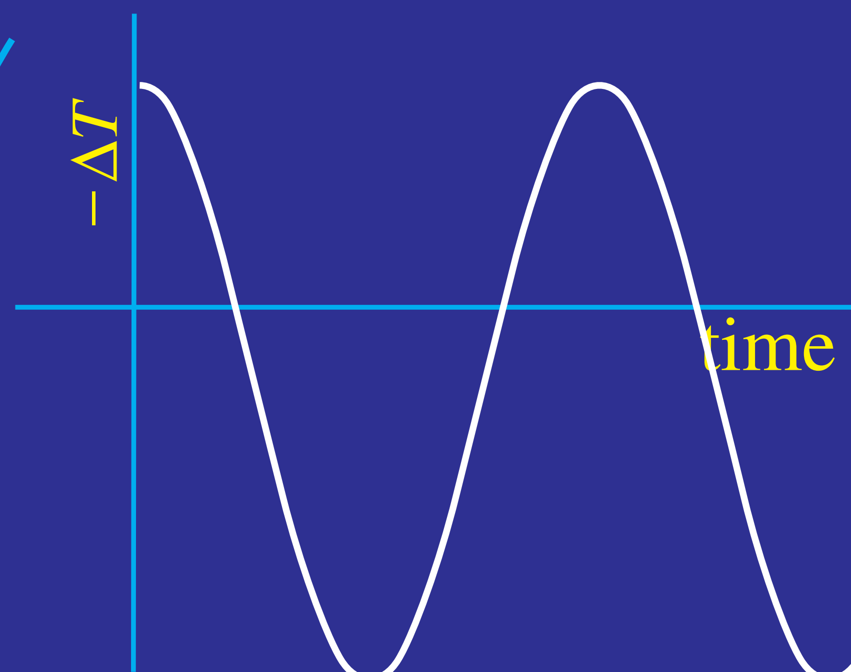

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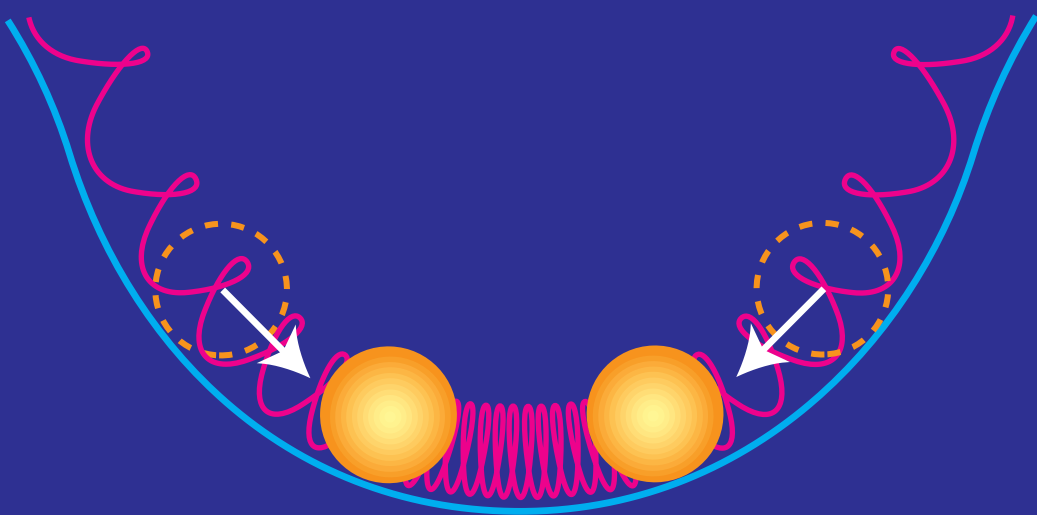
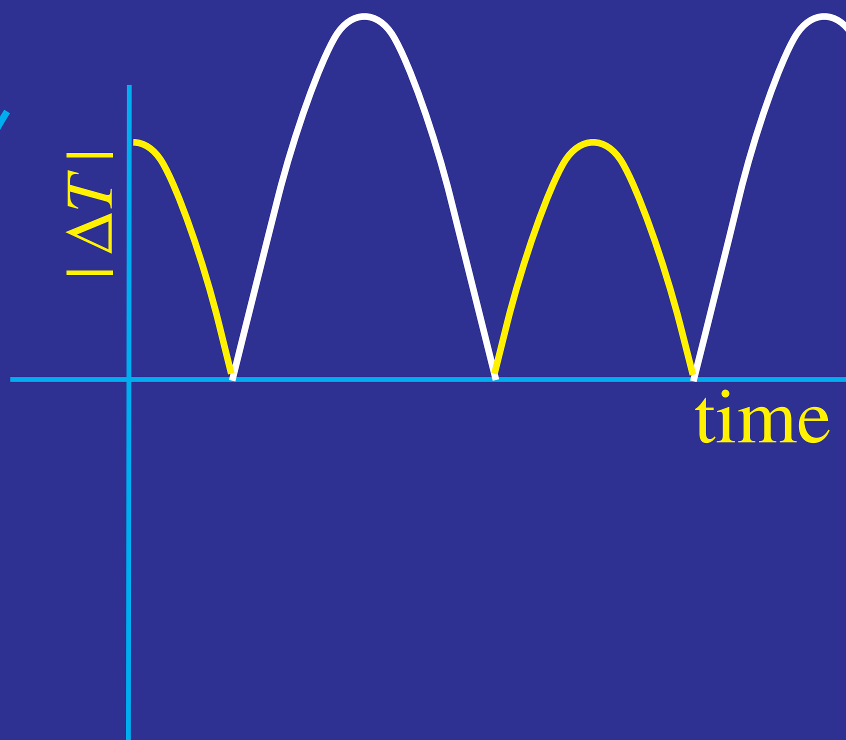
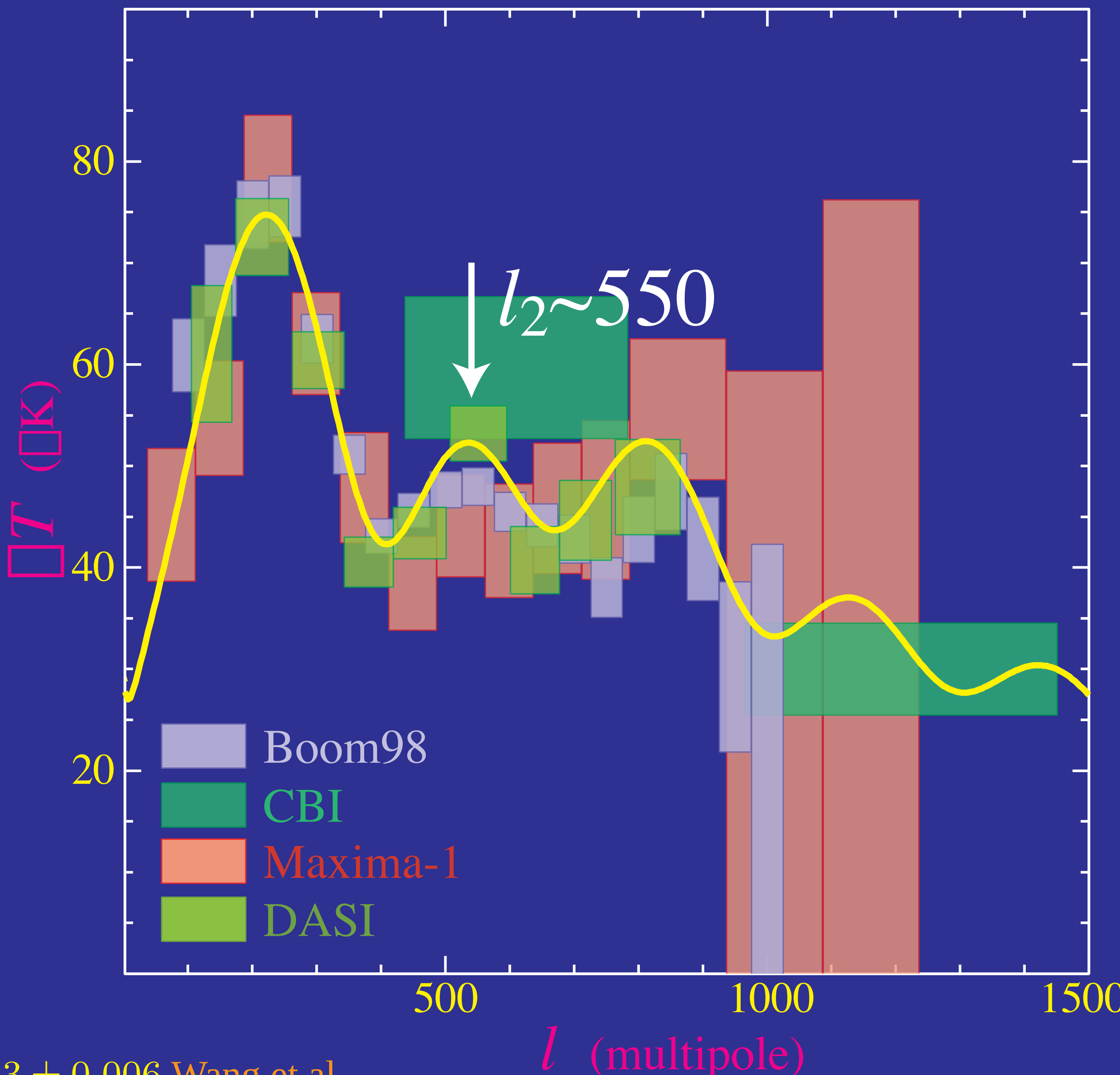
e.g. relative suppression of second peak
boosting of third peak





# Baryons in the Power Spectrum

# BBN Baryon-Photon Ratio




$\Omega_b h^2 = 0.0023 \pm 0.006$ Wang et al.

# Matter-Radiation Ratio

# Radiation Driving

- Matter-to-radiation ratio

$$\frac{\rho_m}{\rho_r} \approx 24\Omega_m h^2 \left( \frac{a}{10^{-3}} \right)$$

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- Decay is timed precisely to drive the oscillator – 5$\times$ the amplitude of the Sachs-Wolfe effect!
- Effect goes away as expansion becomes matter dominated. Fundamentally tests whether energy density driving expansion is smooth at recombination.

# Radiation and Dark Matter

- Radiation domination:

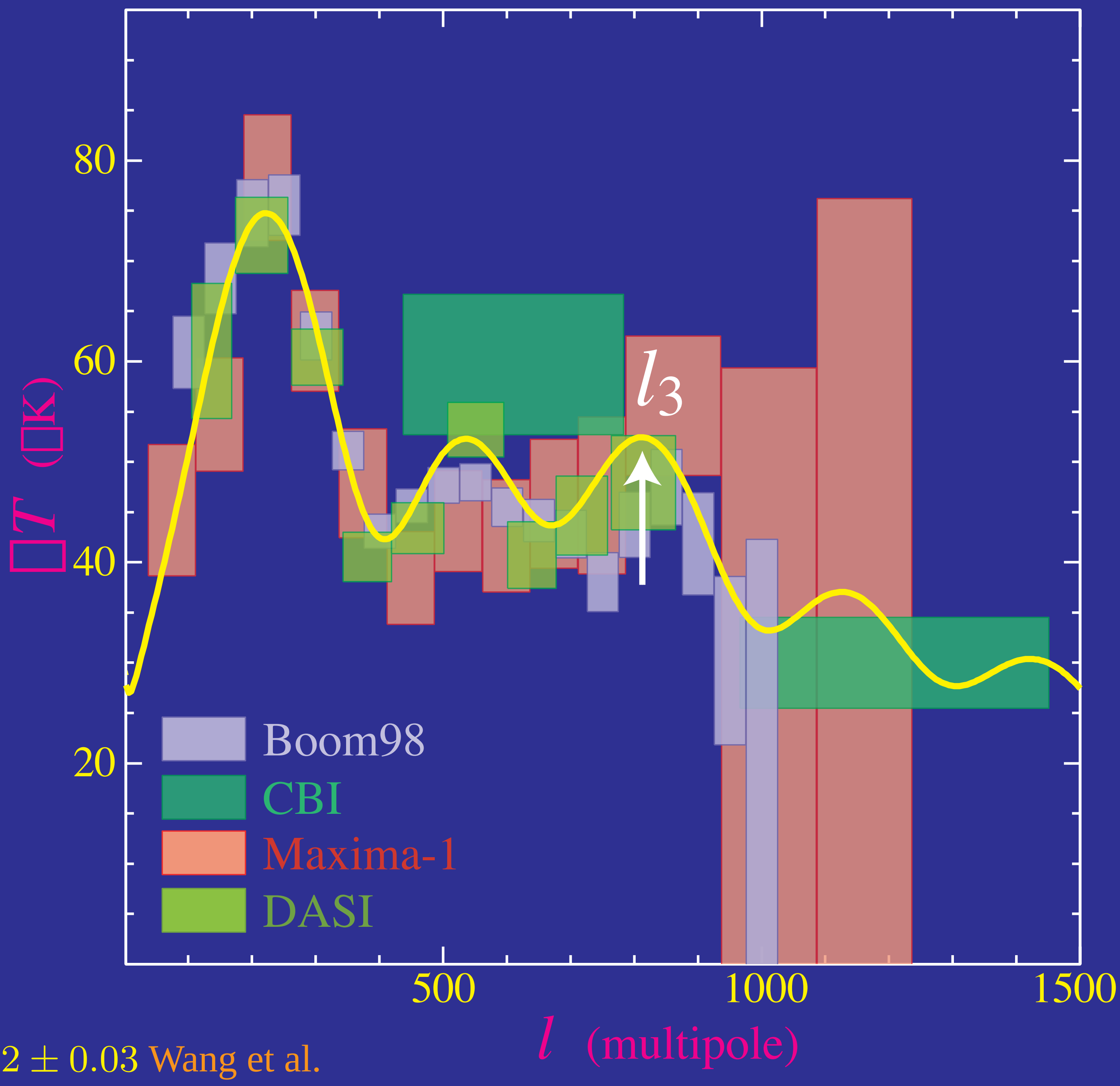
  potential wells created by CMB itself

- Pressure support $\Rightarrow$ potential decay $\Rightarrow$ driving

- Heights measures when dark matter dominates

# Dark Matter in the Power Spectrum

# Dark Matter in the Data




$\Omega_{\rm dm} h^2 = 0.12 \pm 0.03$ Wang et al.

# Damping Tail

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$$\lambda_C = \dot{\tau}^{-1} \quad \text{where} \quad \dot{\tau} = n_e \sigma_T a$$

  is the conformal opacity to Thomson scattering
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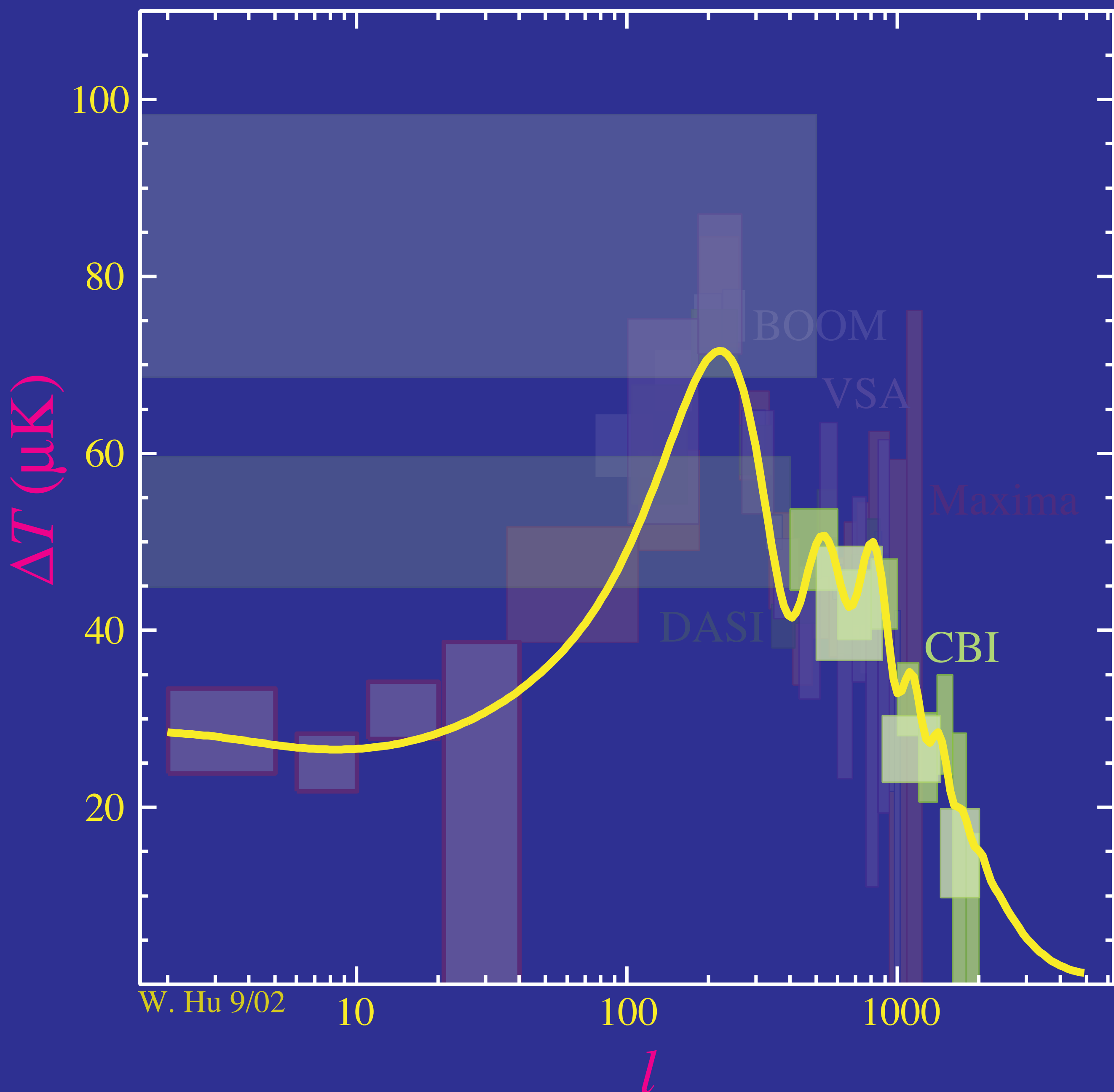
- Fundamental consistency check, e.g. expansion rate at recombination, fine structure constant.

# Damping Tail Measured



# Further Implications of Damping

- CMB anisotropies $\sim 10\%$ polarized

  dissipation $\longrightarrow$ viscosity $\longrightarrow$ quadrupole

  quadrupole $\longrightarrow$ linear polarization

- Secondary anisotropies are observable at arcminute scales

  dissipation $\longrightarrow$ exponential suppression of primary anisotropy $\longrightarrow$ uncovery of secondary anisotropy from CMB photons traversing the large scale structure of the universe

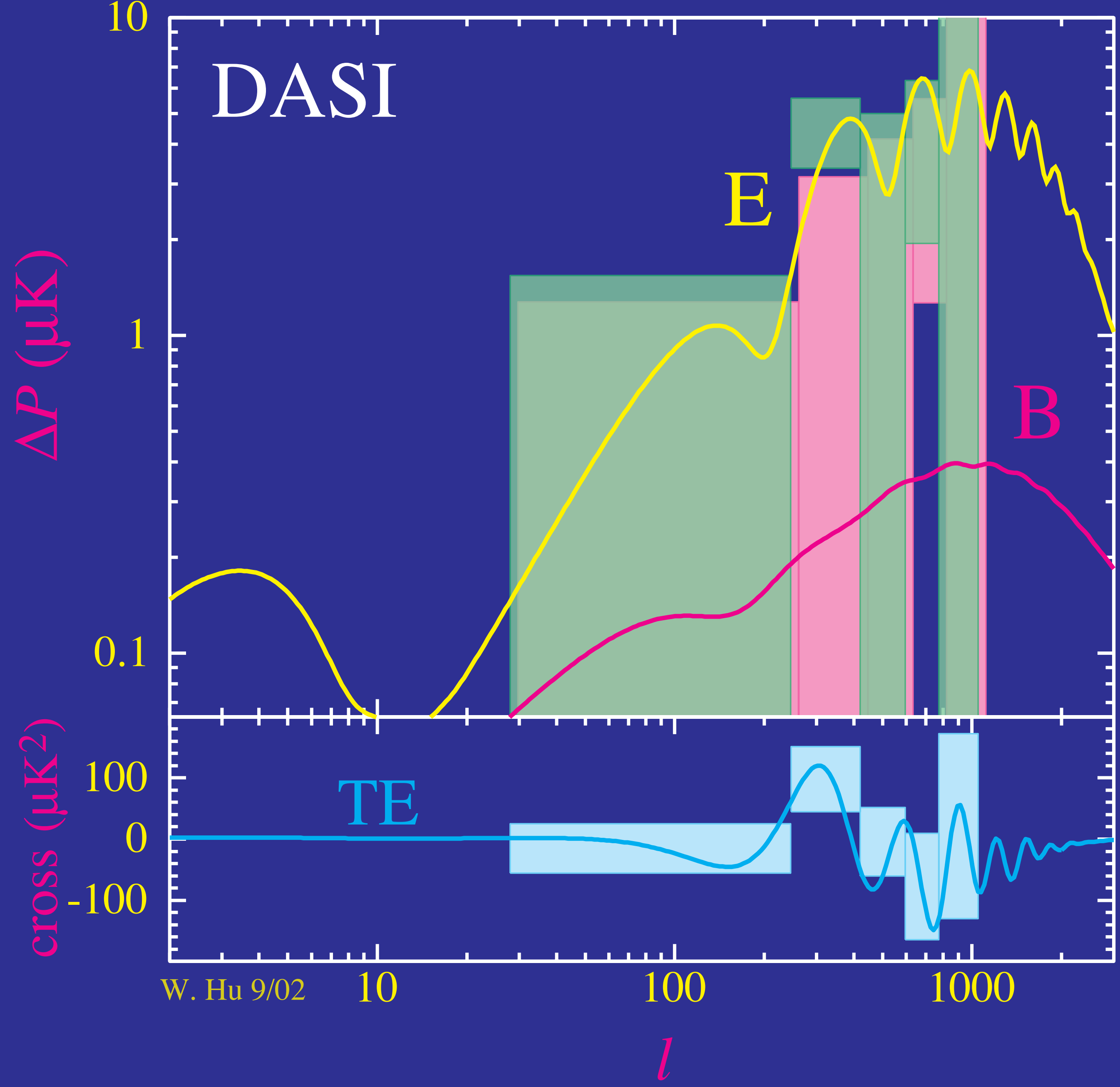
# Polarization

# Polarization from Thomson Scattering

- Quadrupole anisotropies scatter into linear polarization

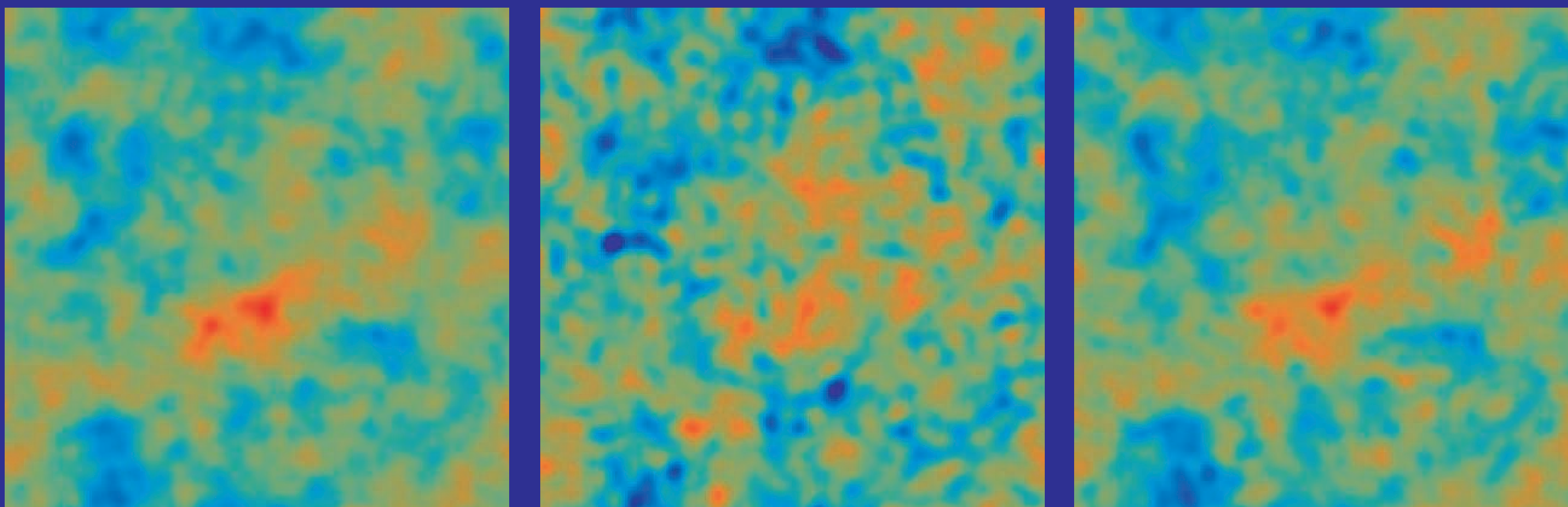
aligned with
cold lobe

# First Detection of Polarization!



# Mapping the Dark Sector

- Gravitational lensing of CMB correlates multipoles
- Reconstruct mass from multipole pairs



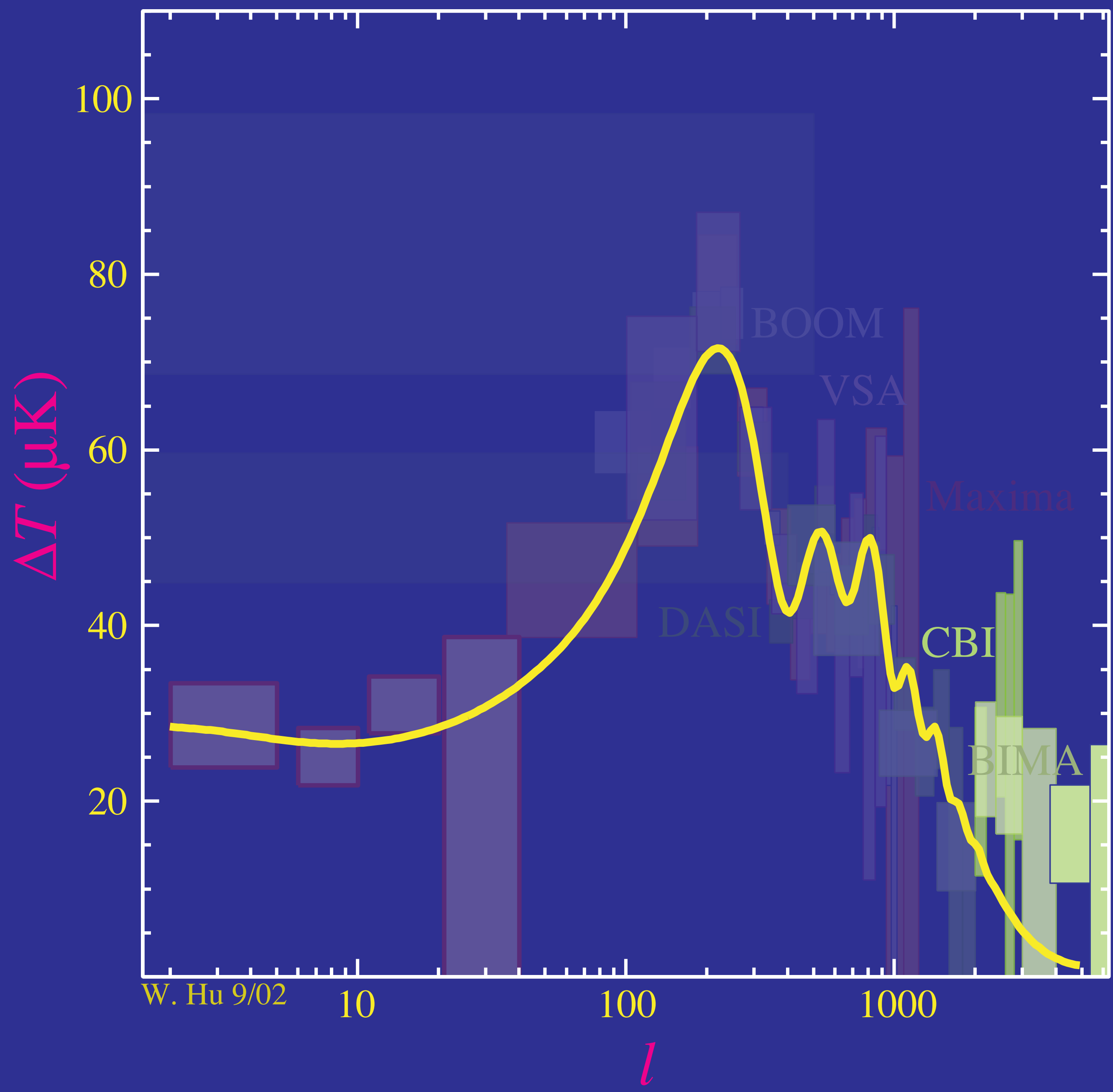
mass temp. reconstruction EB pol. reconstruction

100 sq. deg; 4' beam; 1μK-arcmin

Hu & Okamoto (2002) [earlier work: Guzik et al 2000; Benabed et al 2001]

# Secondary Anisotropies

# Secondary Anisotropy?



# Sensitivity of SZE Power

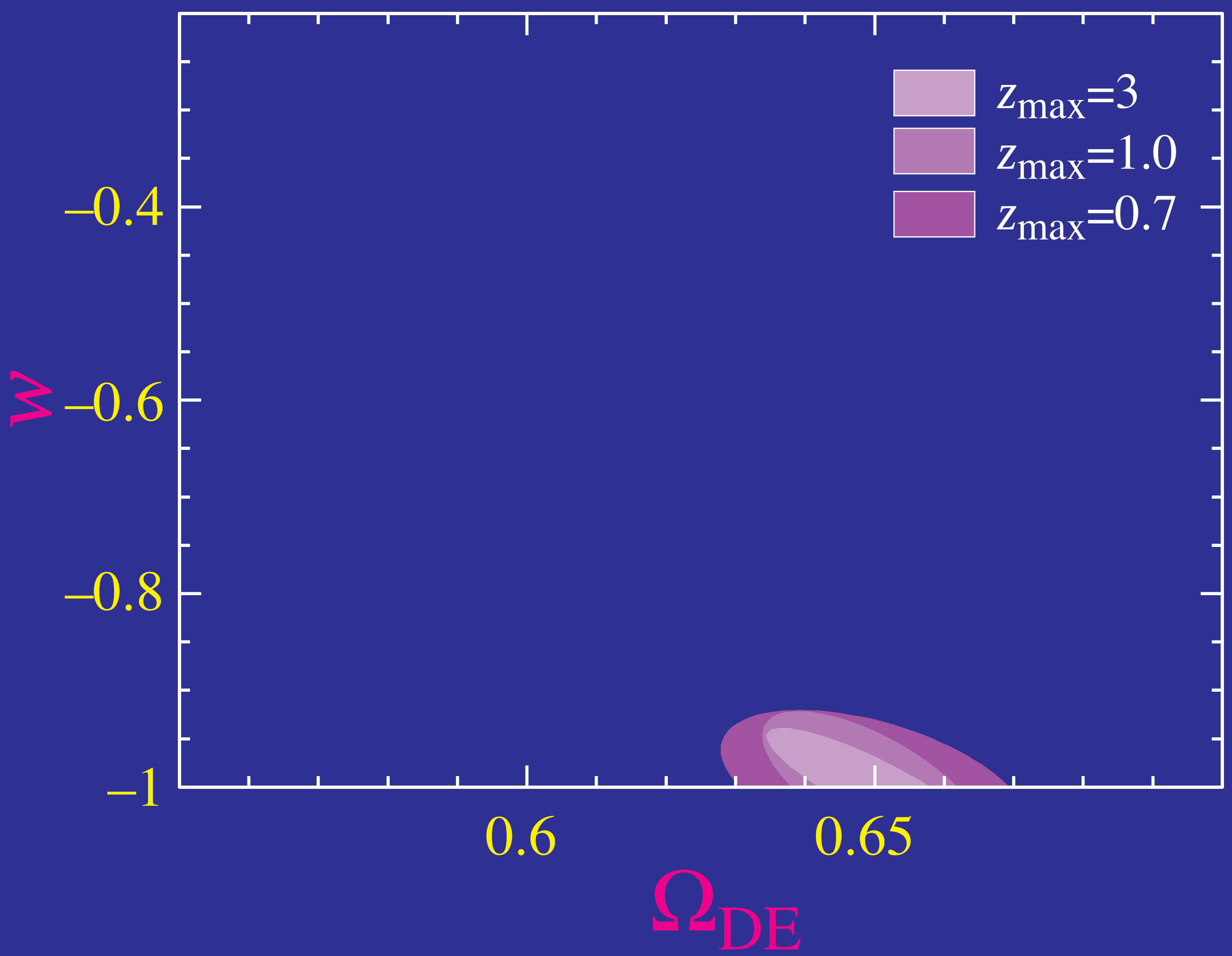
- Amplitude of fluctuations

# Counting Halos → Dark Energy

- Halo abundance exponentially sensitive to growth rate

# Projected Constraints

- Studies of $M$>2.5 x $10^{14}$ $M_{\odot}$ (Haiman et al. 2000; Hu & Kravstov)
- All other parameters known: mass-observable relations!



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  damping & polarization: expansion rate & recombination
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- Precision polarization and secondary anisotropy for the two ends of time: inflation/origins & dark energy/first objects