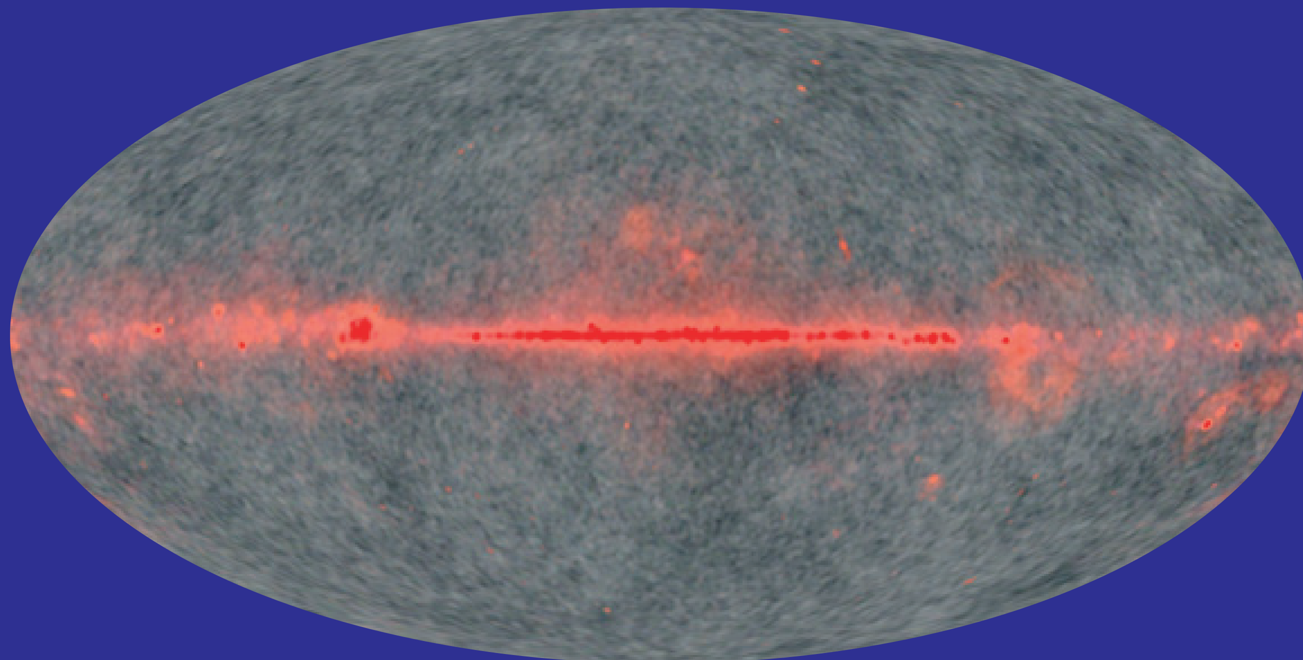
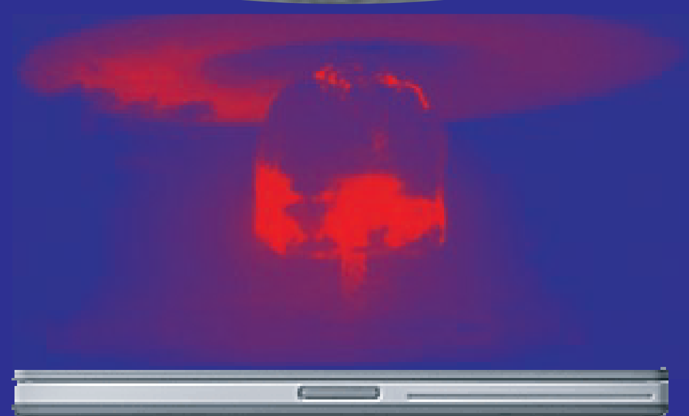
The AfterMap





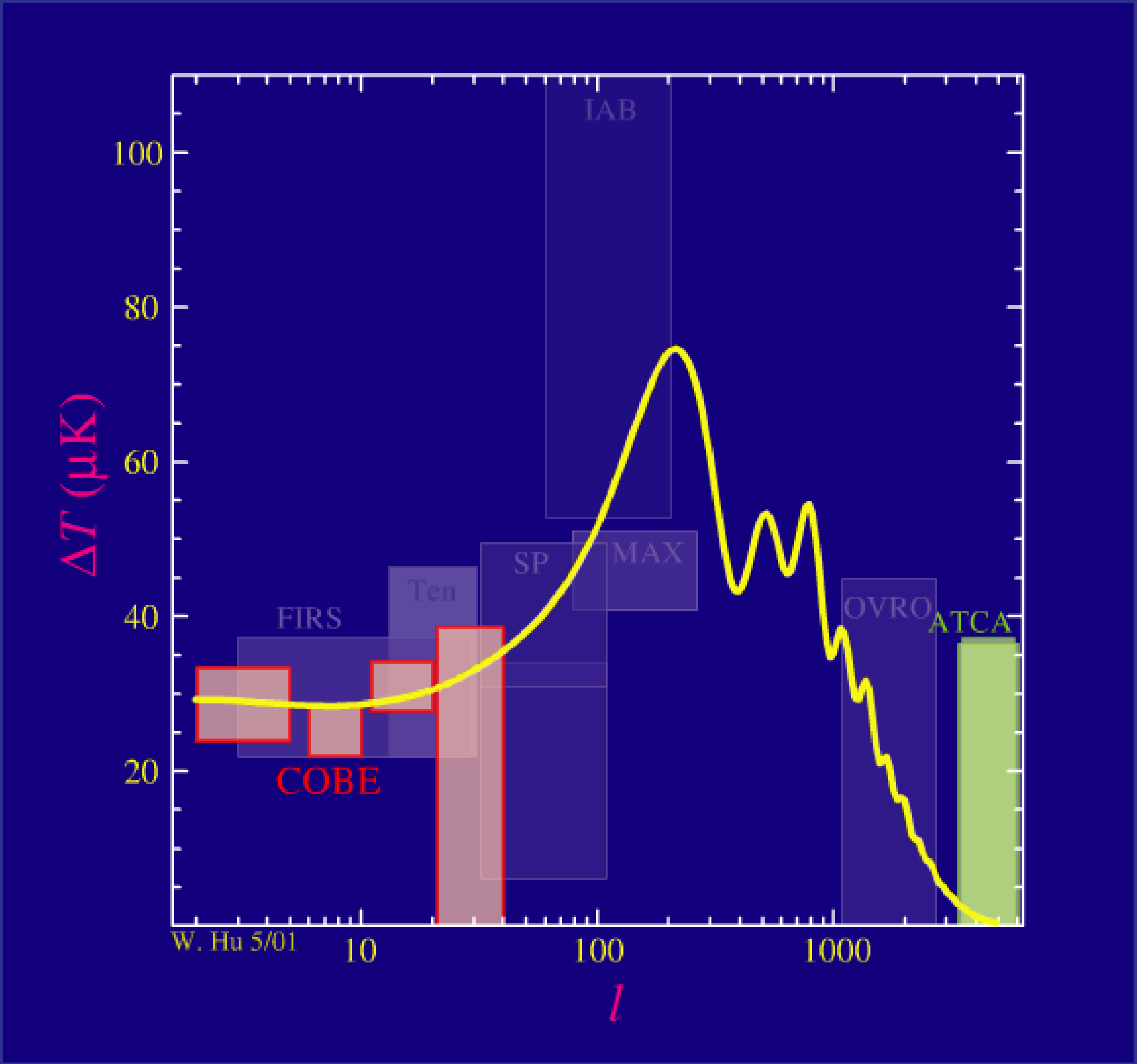
Wayne Hu

EFI, February 2003

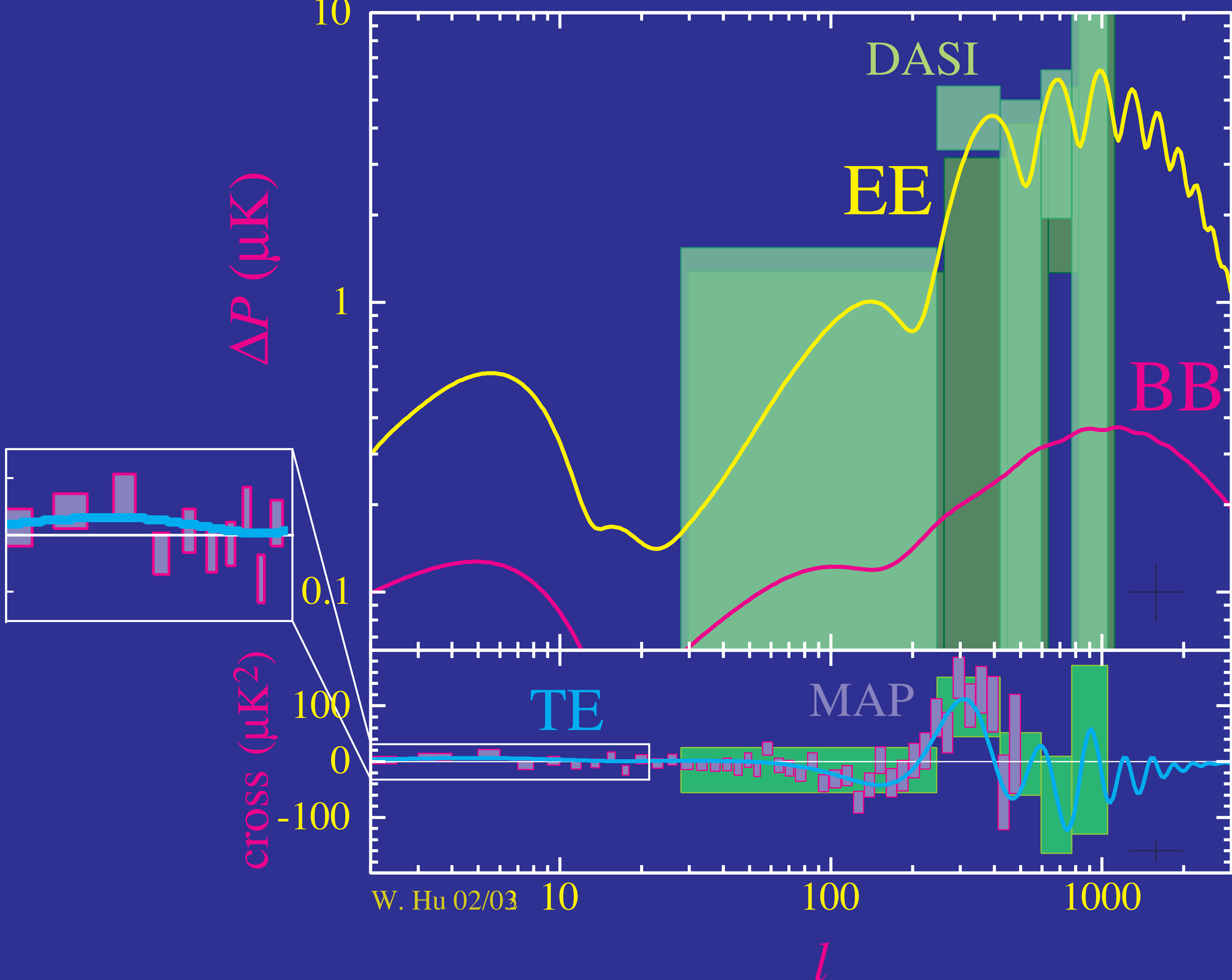
Outline

- Connections to the Past
  - What does MAP alone add to the cosmology?
  - What role do other anisotropy experiments still have to play?
  - How do you use the MAP analysis to go beyond the standard cosmological model?
- Thoughts on the Future
  - Ionization history dependence of the polarization
  - Gravitational wave studies with polarization
  - Glitch studies with polarization
  - Indirect implications of reionization for structure

Theorist's Time-Ordered Data



MAP Detection of Correlation



Before and AfterMap

- Parameter Estimates (1σ range)

Peak Parameters	Before (Wang et al; Knox et al)	MAP (Spergel et al)
ℓ_A	$300 - 308$	$297 - 301$
$\Omega_m h^2$	$0.118 - 0.135$	$0.12 - 0.16$
$\Omega_b h^2$	$0.020 - 0.026$	$0.023 - 0.025$
Initial Spectrum		
n_s	$0.93 - 1.05$	$0.95 - 1.03$
Reionization		
τ	$0 - 0.1$	$0.1 - 0.24$

- Previous experiments both precise and accurate on peak parameters!
- Importantly, the extended range in previous experiments ℓ improves $\Omega_m h^2$, consequences for dark energy

Acoustic Basics

- Continuity Equation: (number conservation)

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

where $\Theta = \delta n_\gamma / 3 n_\gamma$ is the temperature fluctuation with $n_\gamma \propto T^3$

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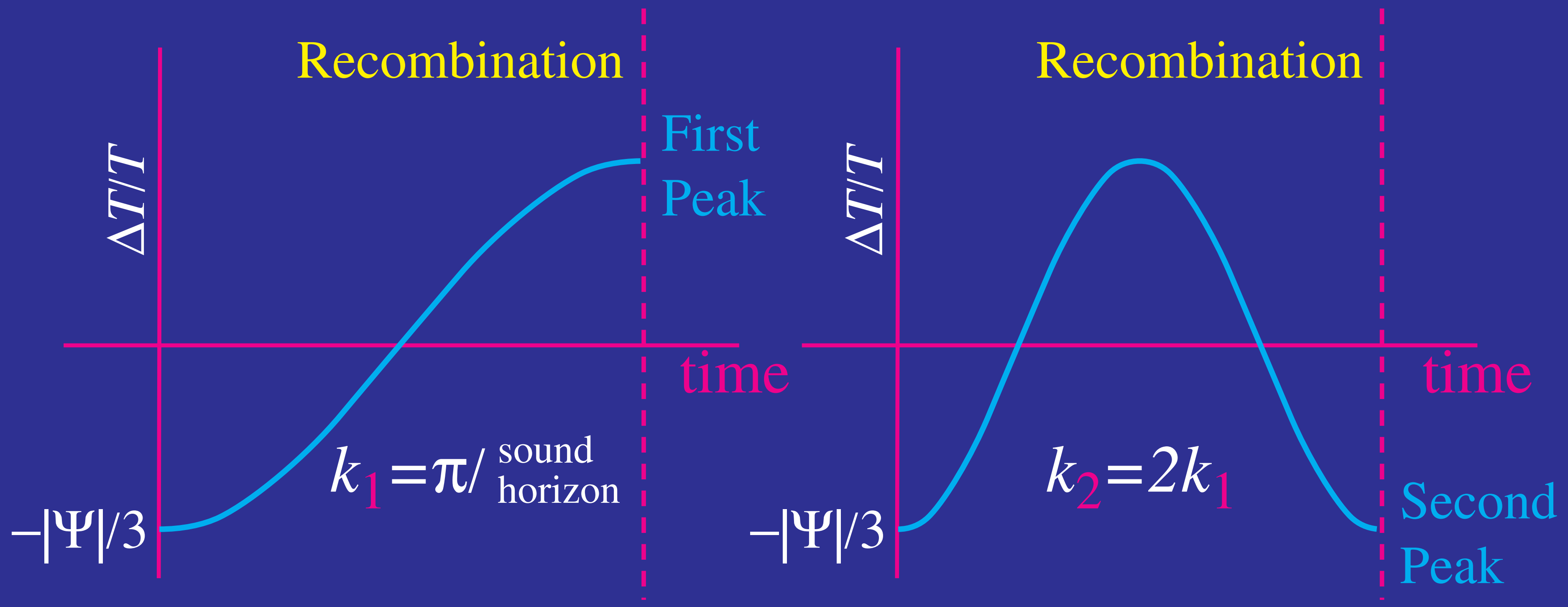
- Modes caught in the extrema of their oscillation will have enhanced fluctuations

$$k_n s_* = n\pi$$

yielding a fundamental scale or frequency, related to the inverse sound horizon and series dependent on adiabatic assumption

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

$$
\begin{aligned}
\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

$$\theta_A \approx \frac{\eta_*}{\eta_0}$$

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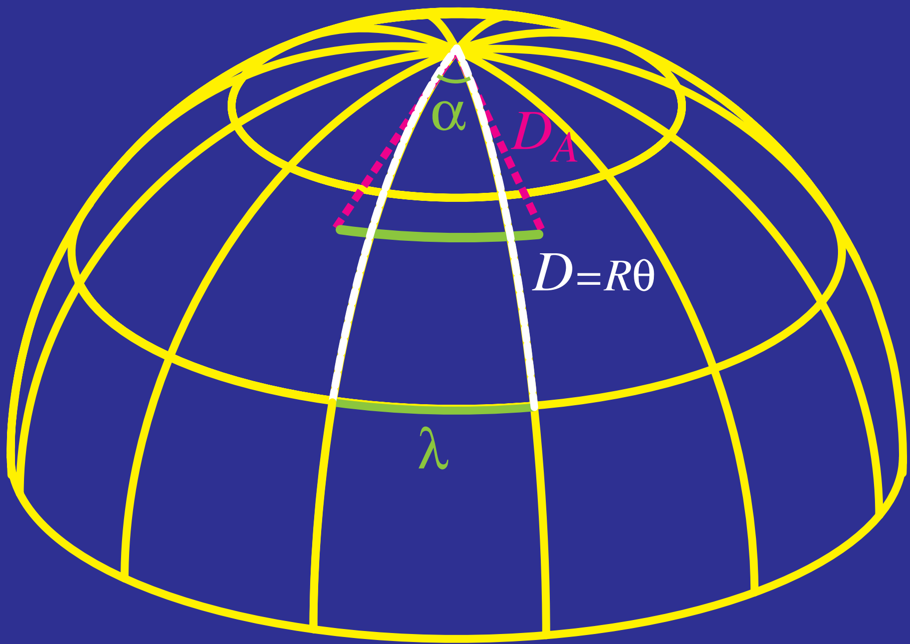
- In a matter-dominated universe $\eta \propto a^{1/2}$ so $\theta_A \approx 1/30 \approx 2^\circ$ or

$$\ell_A \approx 200$$

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 by the background...
- Future: gravitational lensing of large-scale structure

Using the MAP Constraint

- Universe is neither fully matter dominated at recombination nor at the present due to radiation and dark energy
- Given a recombination epoch a_* (depends mainly on temperature and atomic physics) calculate the sound horizon

$$s_* \equiv \int c_s d\eta = \int_0^{a_*} da \frac{c_s}{a^2 H}$$

  note that this depends mainly on the expansion rate H at a_*, i.e. the matter-radiation ratio.
- Given a dark energy model, calculate the comoving distance to a_*

$$D = \int_{a_*}^{1} da \frac{1}{a^2 H}$$

- Given a curvature calculate the angular diameter distance $D_A = R \sin(D/R)$

Using the MAP Constraint

- Put it together:

$$\ell_A \equiv \frac{\pi D_A}{s_*}$$

- Note that H_0 always cancels in the ratio, but that with both radiation and dark energy
- Simple model: around $\Omega_m h^2 = 0.14$, $\Omega_b h^2 = 0.024$, $\Omega_{DE} = 0.73$, $w_{DE} = -1$, $\alpha = \alpha_0$

$$\frac{\Delta \ell_A}{\ell_A} = 1.2 \frac{\Delta \Omega_{\rm tot}}{\Omega_{\rm tot}} - 0.11 \frac{\Delta \Omega_{DE}}{\Omega_m} + 0.1 \Delta w_{DE}$$
$$- 0.25 \frac{\Delta \Omega_m h^2}{\Omega_m h^2} + 0.083 \frac{\Delta \Omega_b h^2}{\Omega_b h^2} + 2.3 \frac{\Delta \alpha}{\alpha}$$

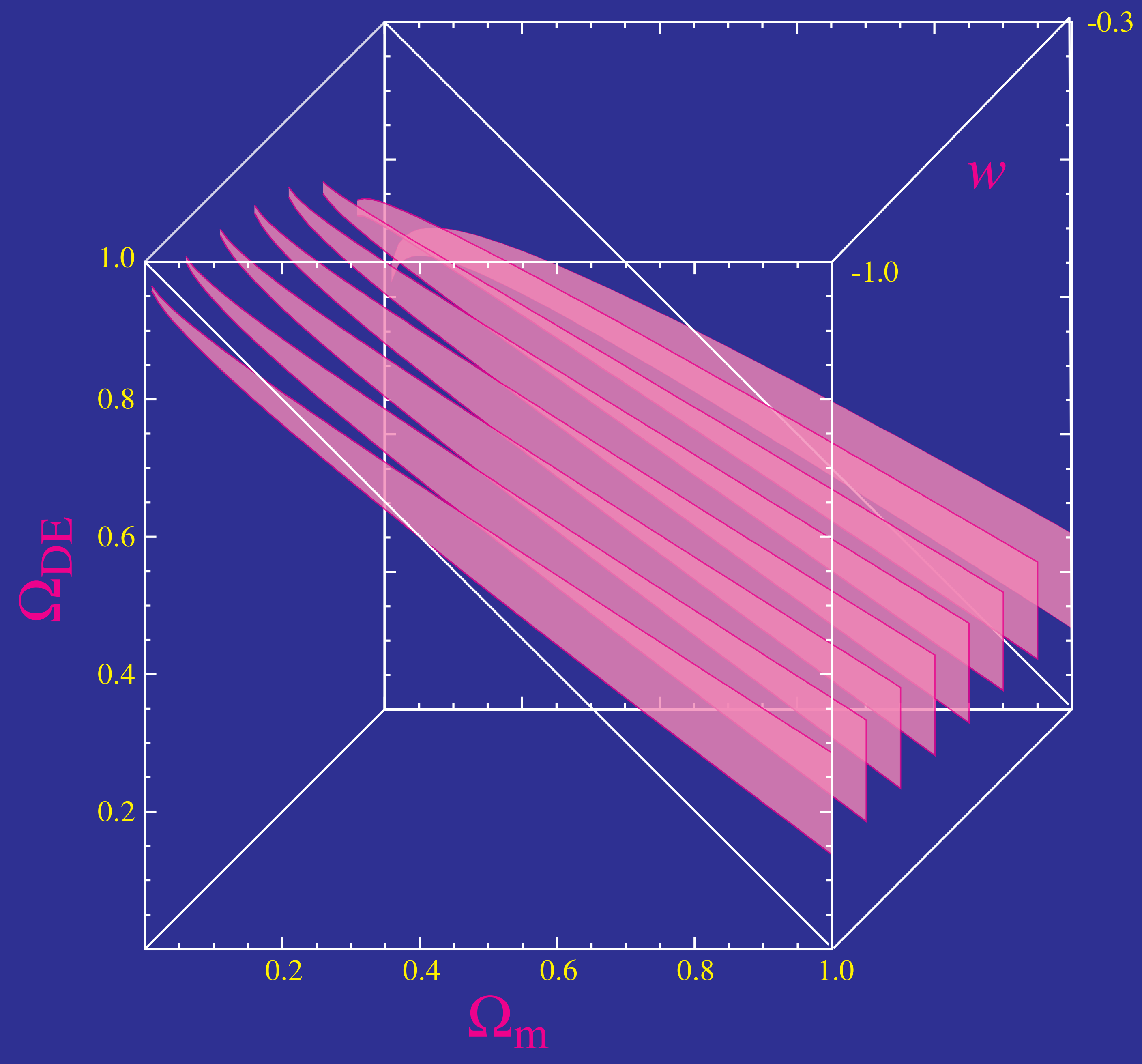
- Leading source of error to $\Omega_{\rm tot} = \Omega_m + \Omega_{DE}$, Ω_{DE} is from $\Omega_m h^2$

Dark Energy and the Peaks

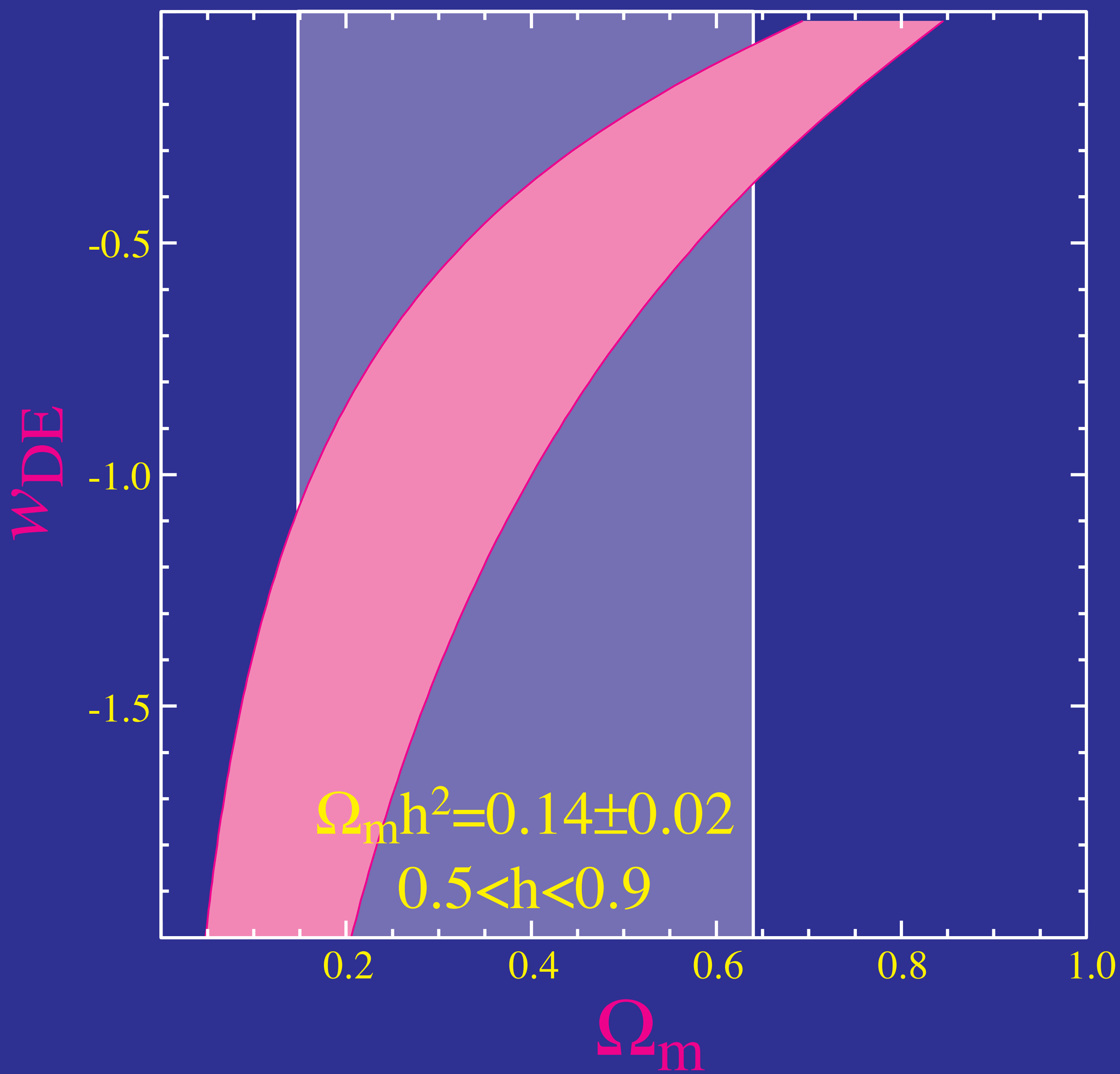
- Peaks shift to lower multipoles as the dark energy density increases

Dark Energy

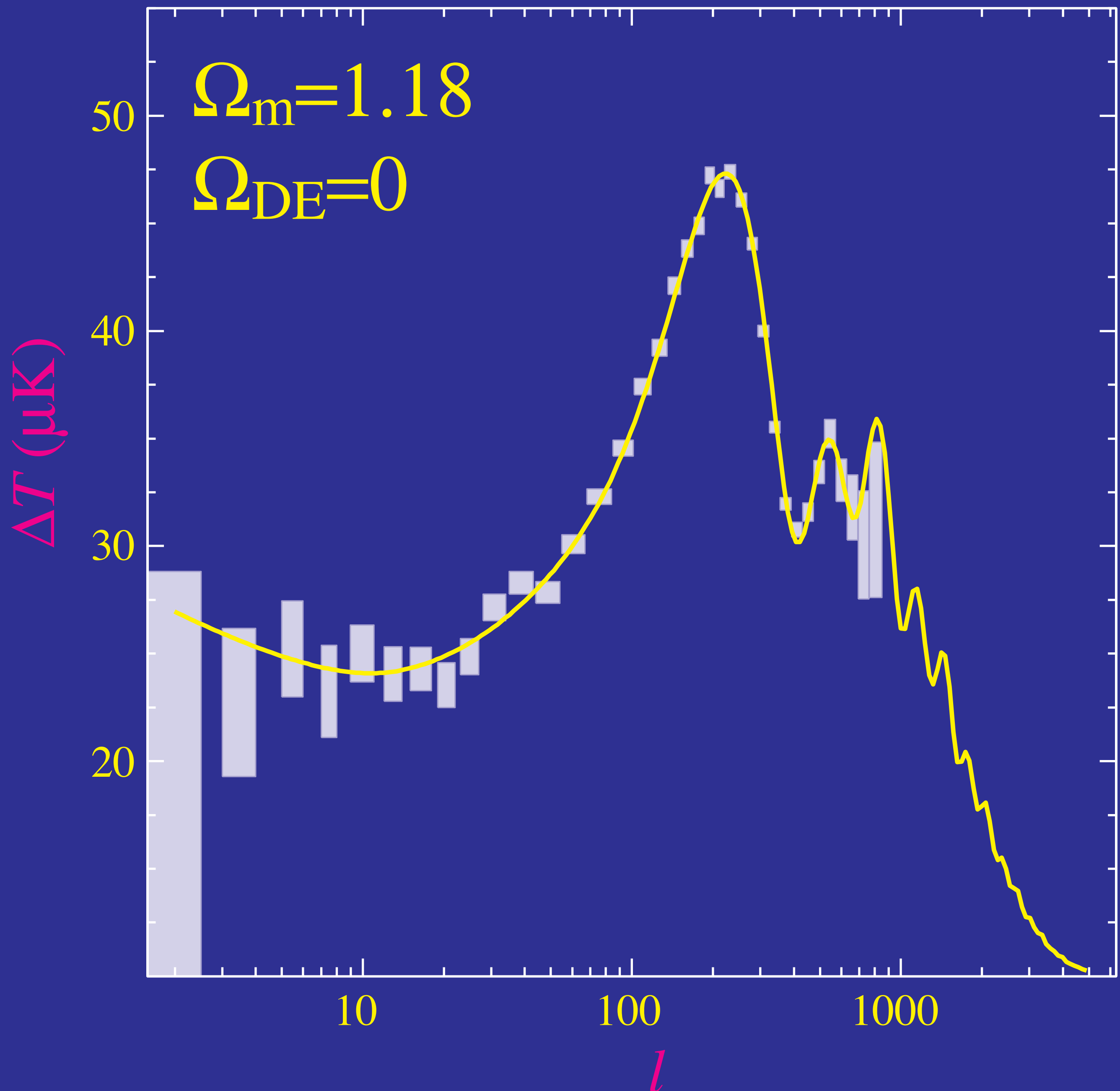
Dark Cube



Equation of State



Peak Degeneracy



Equation of State

- Degeneracy is broken at low multipoles, ISW effect

Glitches

- 3 glitches in the otherwise smooth power spectra
- Low quadrupole (previously known): clusters out to $z \sim 1$ should share in the low quadrupole making their cosmic polarization even more difficult to detect
- Features at $\ell \sim 40$ and first peak: prove whether they are primordial, dynamic, or systematic with precision polarization: (dynamical effects will add with a different phase in the oscillations, gravitational redshift effects are unpolarized...) likely requires more sensitivity than MAP will achieve

Quadrupoles at Reionization

- Temperature inhomogeneities at recombination which are on scales comparable to the horizon appear as quadrupole anisotropies to the observer

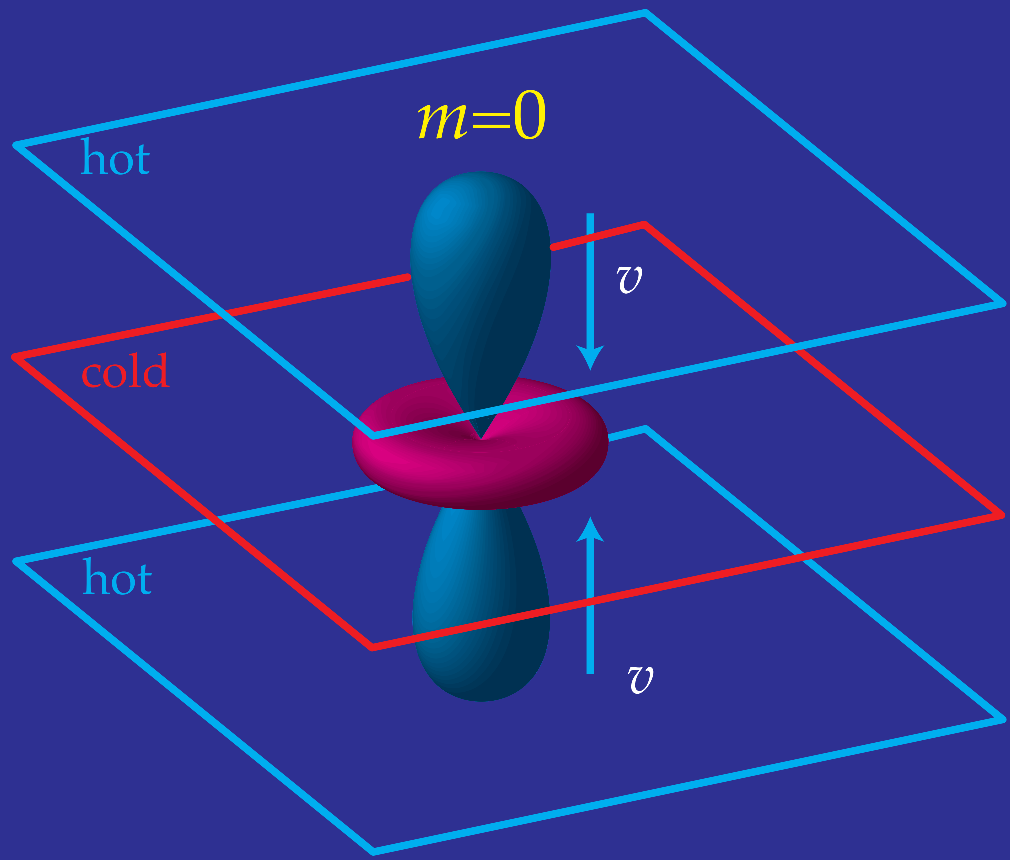
Polarization from Thomson Scattering

- Quadrupole anisotropies scatter into linear polarization

aligned with
cold lobe

Polarization During Reionization

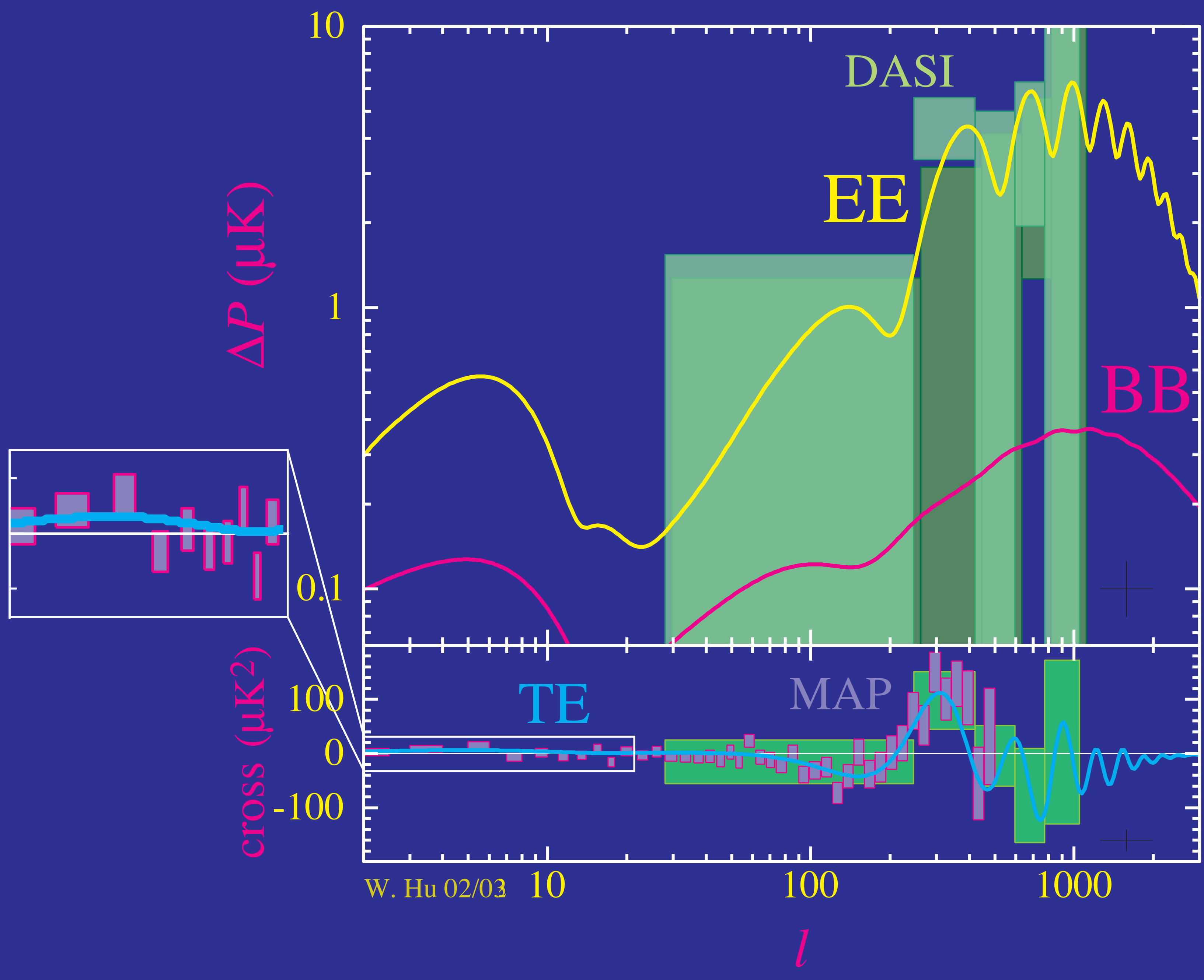
- Polarization is aligned with the cold lobe of the quadrupole and hence correlated with the temperature
- Correlation appears at large angles (angle subtended by horizon)



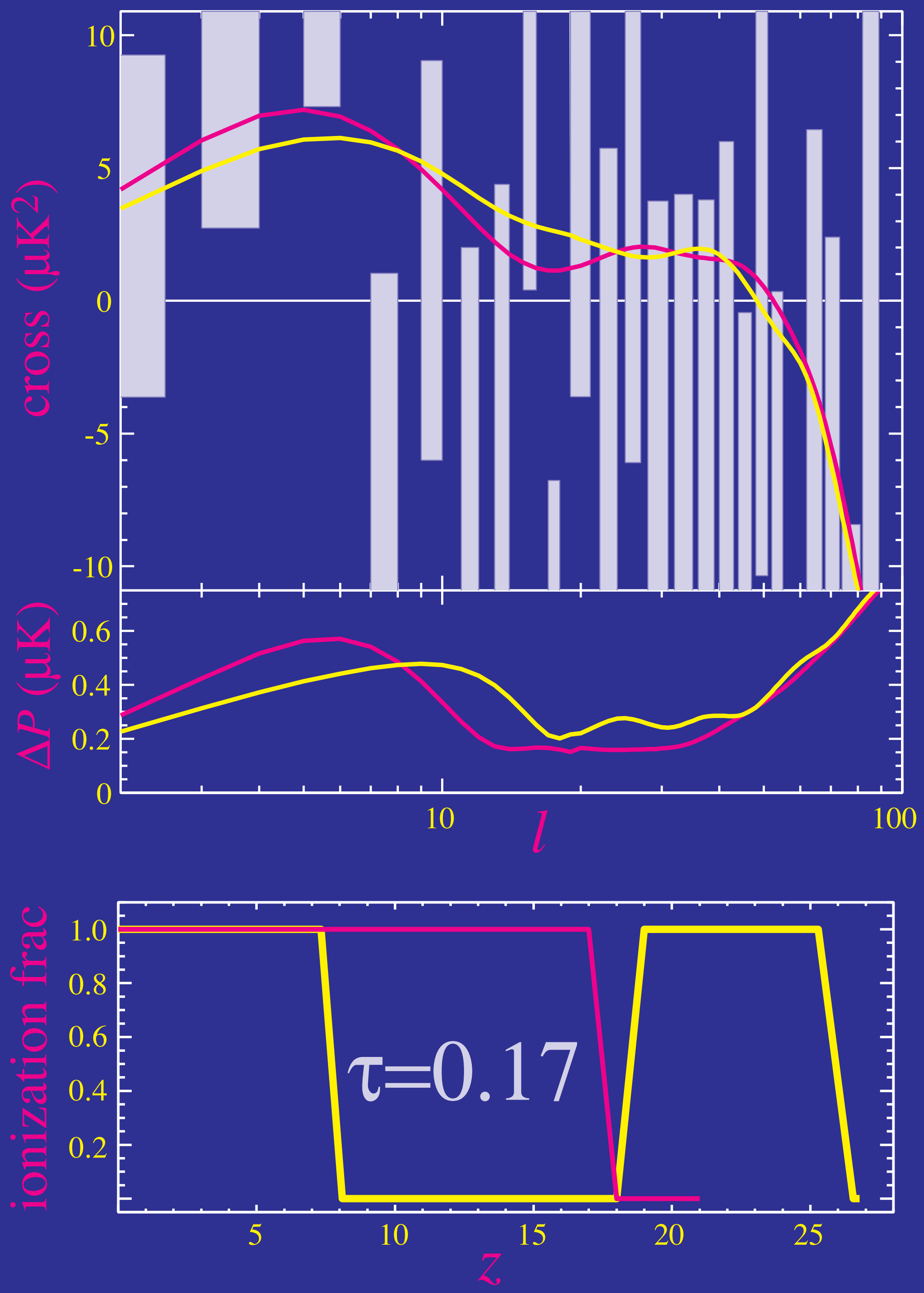
Reionization and Polarization

- Reionization generates large–scale polarization

MAP Detection of Correlation



Reionization History

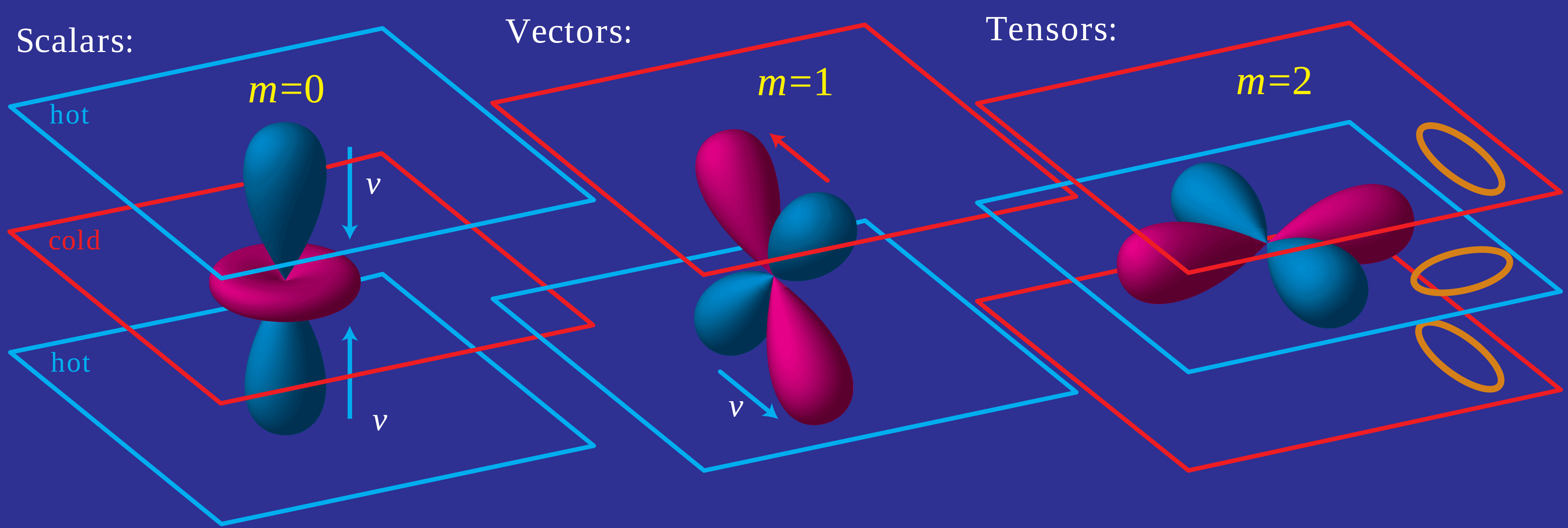


Reionization: Direct Implications

- High optical depth and finite (but small for CMB purposes) neutral hydrogen in SDSS quasar absorption spectra imply complex ionization history Kogut et al
- Measures of τ assuming an incorrect ionization history may be biased at a small but in the future important level for dark energy studies (% level).
- EE modes (polarization auto correlation) intrinsically more sensitive to polarization – potentially can get around bias and study some aspects of the ionization history - bumps on the scale of the horizon whenever optical depth is significant
- Gravitational wave B-mode polarization is larger in the reionization bump than in the recombination bump – easier to measure if not for foregrounds and systematics

Perturbations & Their Quadrupoles

- Orientation of quadrupole relative to wave (**k**) determines pattern
- Scalars (density) $m=0$
- Vectors (vorticity) $m=\pm1$
- Tensors (gravity waves) $m=\pm2$



Hu & White (1997)

Polarization on the Sphere

- Polarization due to gravitational waves follows similarly
- m=±2 quadrupole viewed at different angles

- Difference: no symmetry – Q and U polarization
- Coordinate independent description of polarization

Reionization: Indirect Implications

- Best normalization of structure is from peaks not COBE $Ae^{-\tau}$ fixed. τ errors $(4-7\%)$ smaller than cosmic variance at COBE
- Peaks intrinsically $\sim 20\%$ larger in amplitude raising the normalization.
- For scale invariant spectrum $\sigma_8 = 0.9$
- Large scale structure and Lyα forest clustering spectra suggest a lower amplitude $\sigma_8 = 0.7$. Suggests tilt of $n \sim 0.93$ Spergel et al
- Tension between early reionization which requires high amplitude fluctuations at small scales and indications of tilt which imply low amplitude at small scale

Sensitivity of SZE Power

- Amplitude of fluctuations

Bond et al. (2002); Komatsu & Seljak (2002)

Dark Energy from Cluster Counts

- Cluster abundance depends exponentially on the amplitude of perturbations: measure the dark energy dependence of their growth but $\sigma_8 = 0.7 - 0.9$ is a factor of several uncertainty in abundance

Summary of Things Past

- Verification that the CMB has entered an era of precision and accurate cosmology!
- Parameter measurements based on peak morphology and location can be readily transferred to more exotic cosmologies, e.g. arbitrary dark energy models. Matter radiation ratio dominates the internal error budget; Hubble contant and SN still key to isolating dark energy.
- High ℓ CMB measurements still help pin down key parameters $\Omega_m h^2$ and resolve tilt debate
- Glitches intriguing, polarization a good future test

Summary of Things Future

- Reionization signature in polarization should be stronger in the EE power spectra, potentially resolving gross features in the ionization history and debiasing future normalization measurements. COBE normalization will give way to peak normalization.
- Gravitational wave B-mode may have a stronger signature at low $\ell \sim 10$ than $\ell \sim 100$.
- Tilt indicated only externally, otherwise higher intrinsic amplitude implies more small scale structure, easier to reionize early, more high redshift clusters