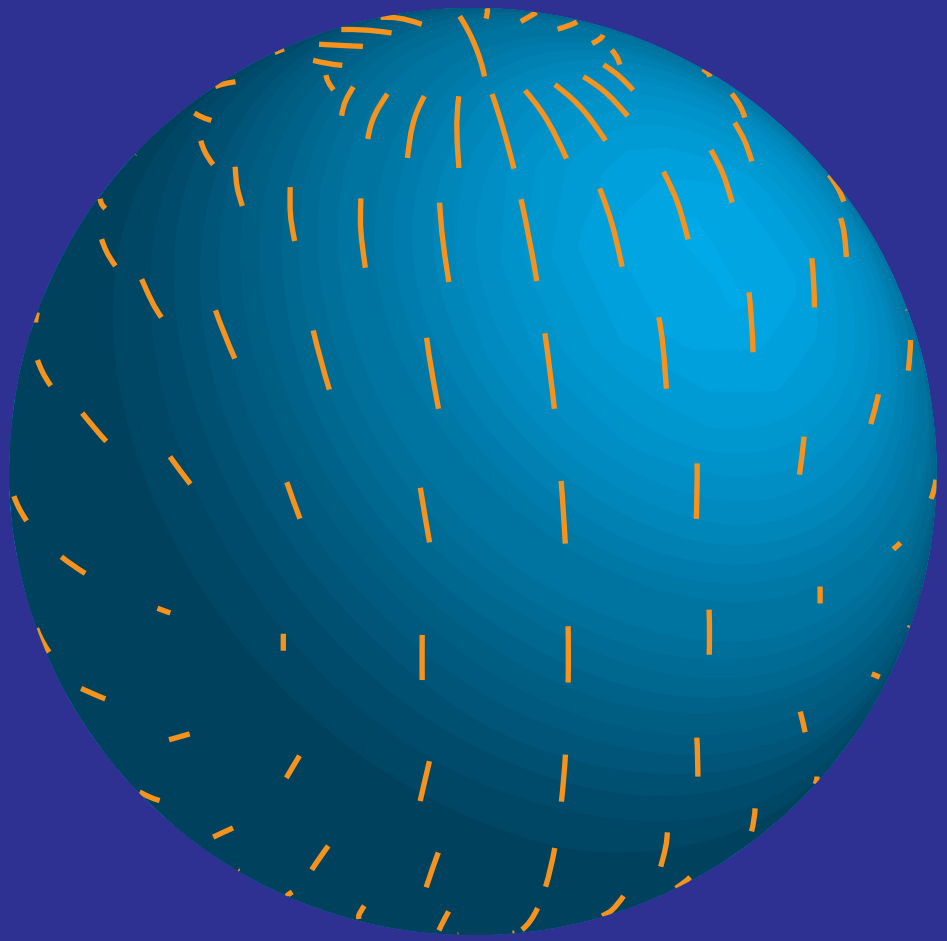
# The Cosmic Microwave Background:



# Theoretical Questions for the Future

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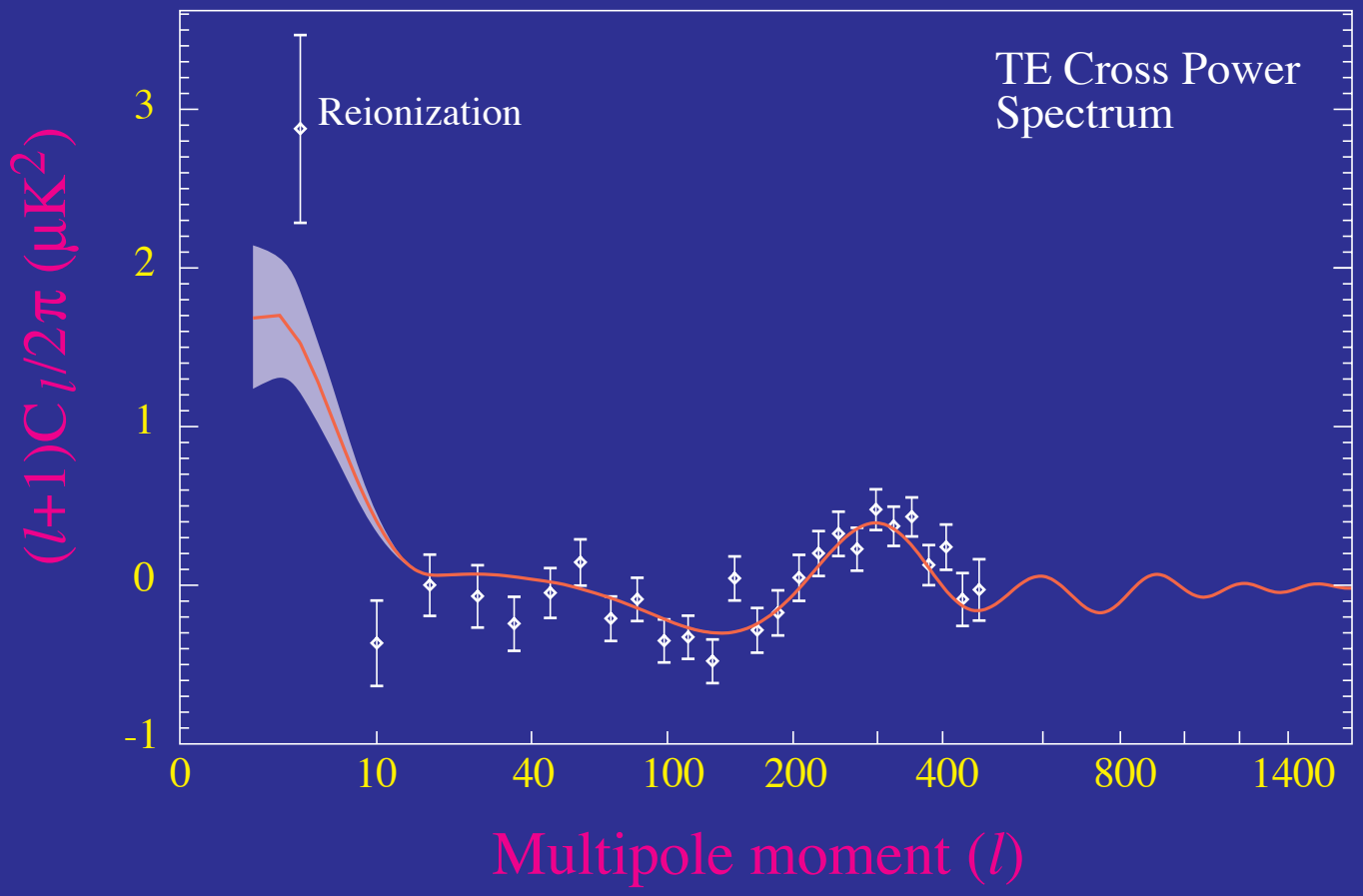
Case Western Reserve University

**1** What can we learn from reionization? does early reionization change prospects for the future?

# Reionization

- Biggest surprise of WMAP: early reionization from temperature polarization cross correlation (central value $\tau$=0.17)

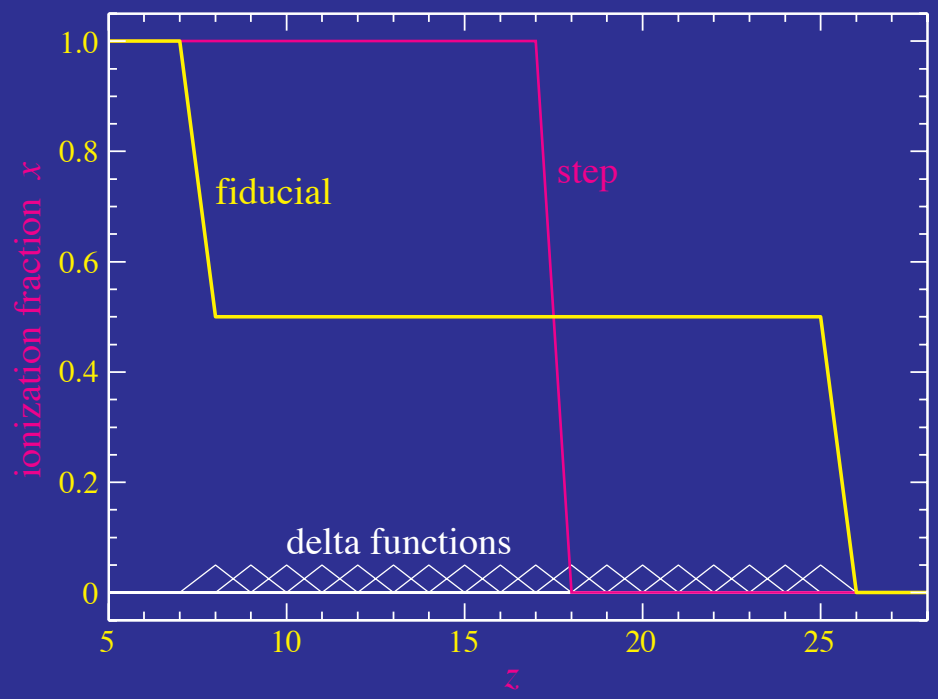


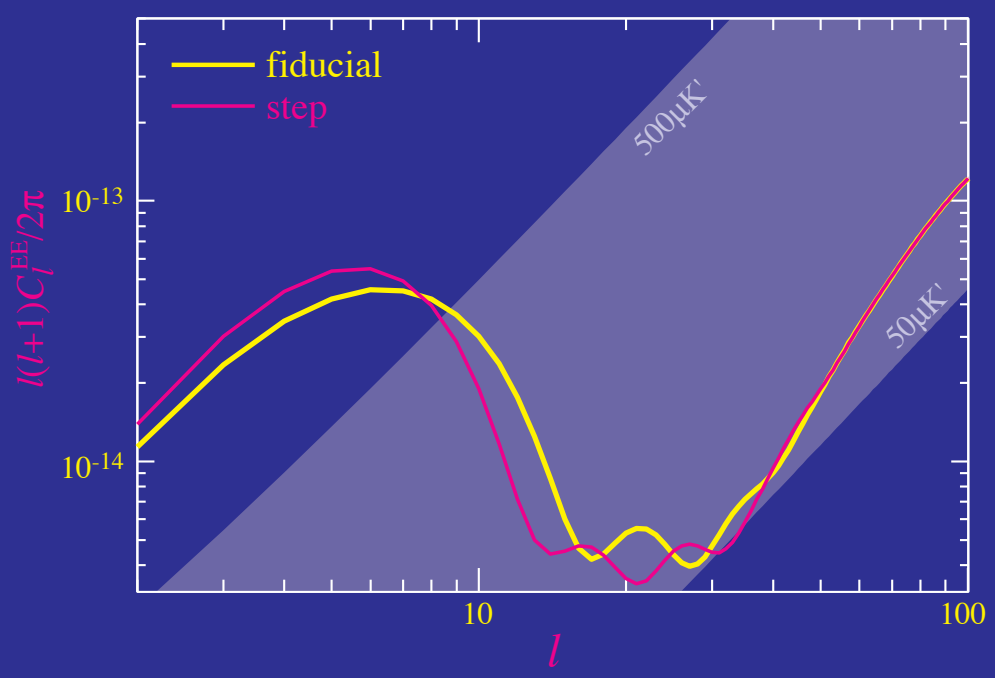

Kogut et al (2003)

# Reionization History

- Polarization provides a unique window to ultra high-z structure (z>15).
- E-spectrum can distinguish ~5 parameters controlling ionization history, determine initial amplitude to 1%

Hu & Holder (2003)

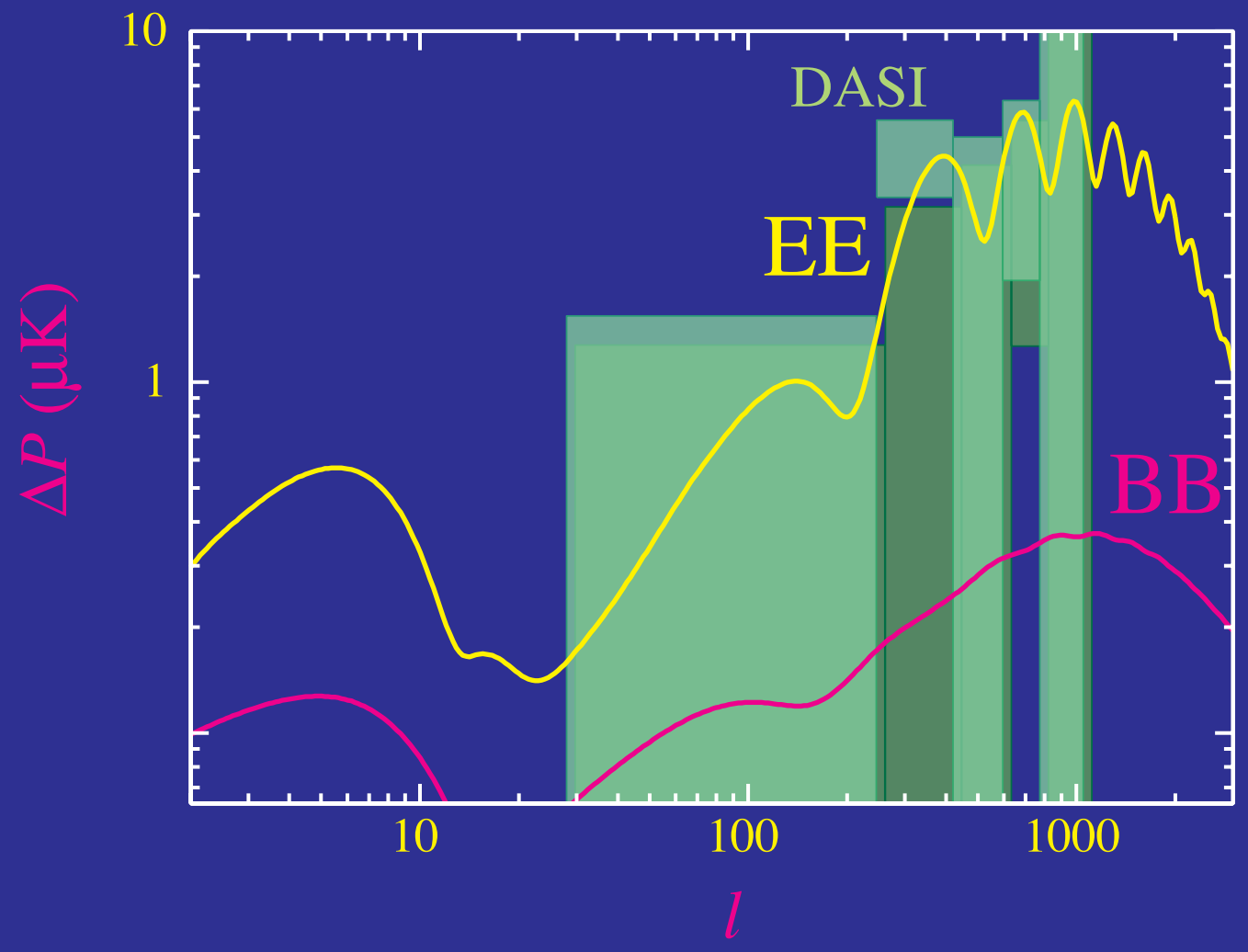



Kaplinghat et al (2003); Cen (2003); Haiman et al (2003); ...

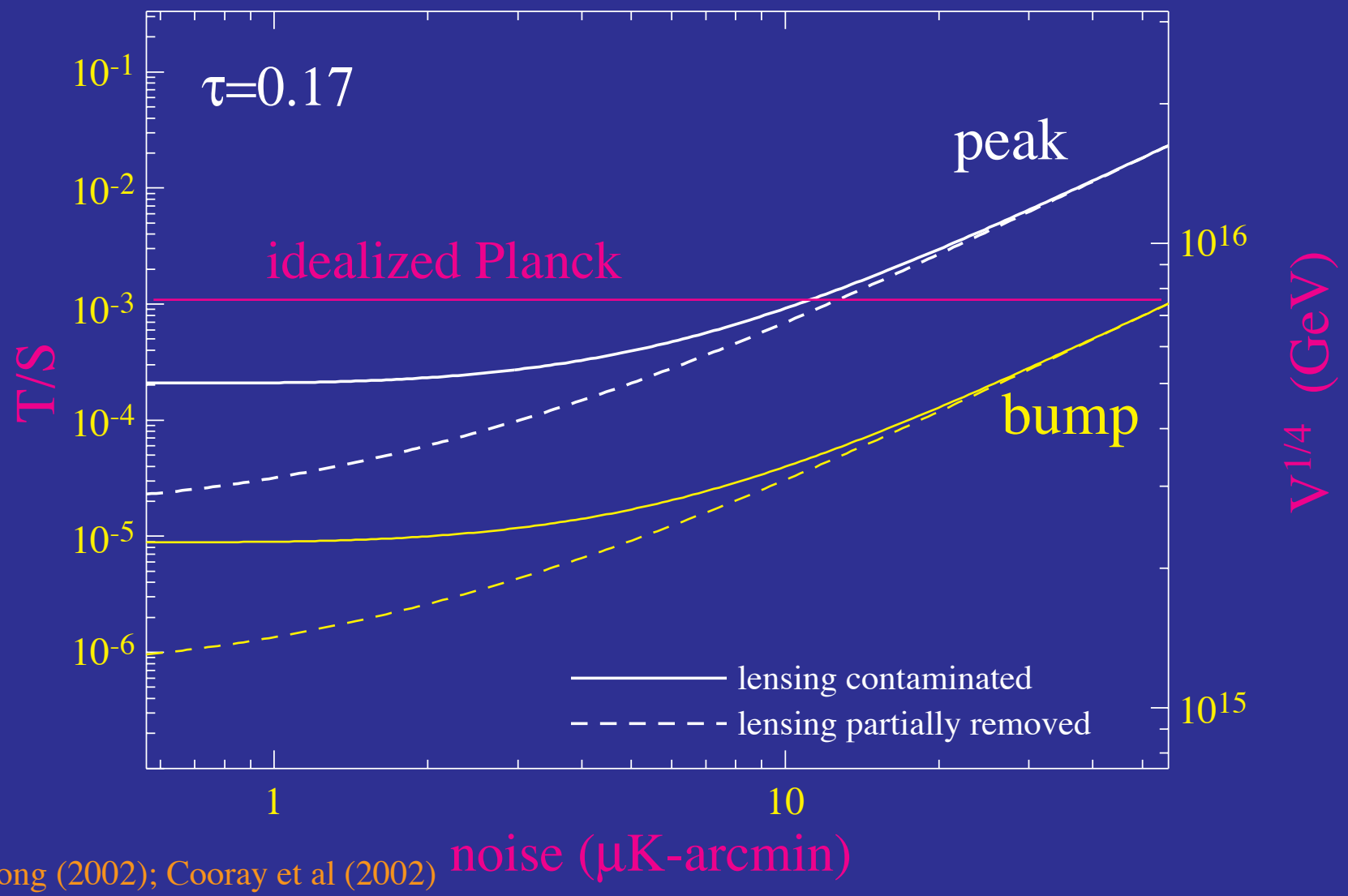
# The B-Bump

- Rescattering of gravitational wave anisotropy generates the B-bump
- Potentially the most sensitive probe of inflationary energy scale



# T/S, Inflation and the B-Bump

- B-bump up to 20x more sensitive to T/S
- In combination with recombination peak, constrain spectrum




Hu (2001)
Knox & Song (2002); Cooray et al (2002)

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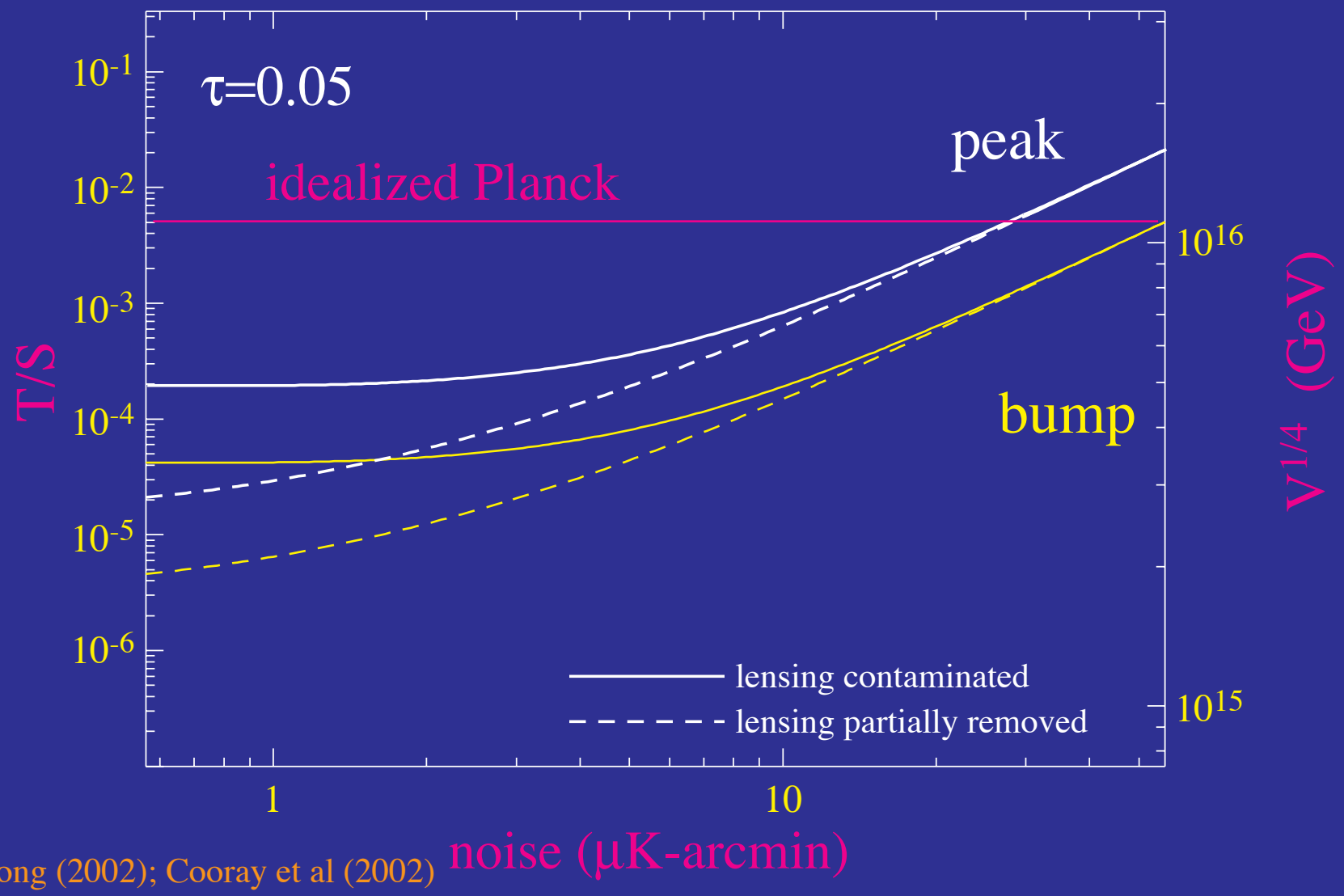


Hu (2001)
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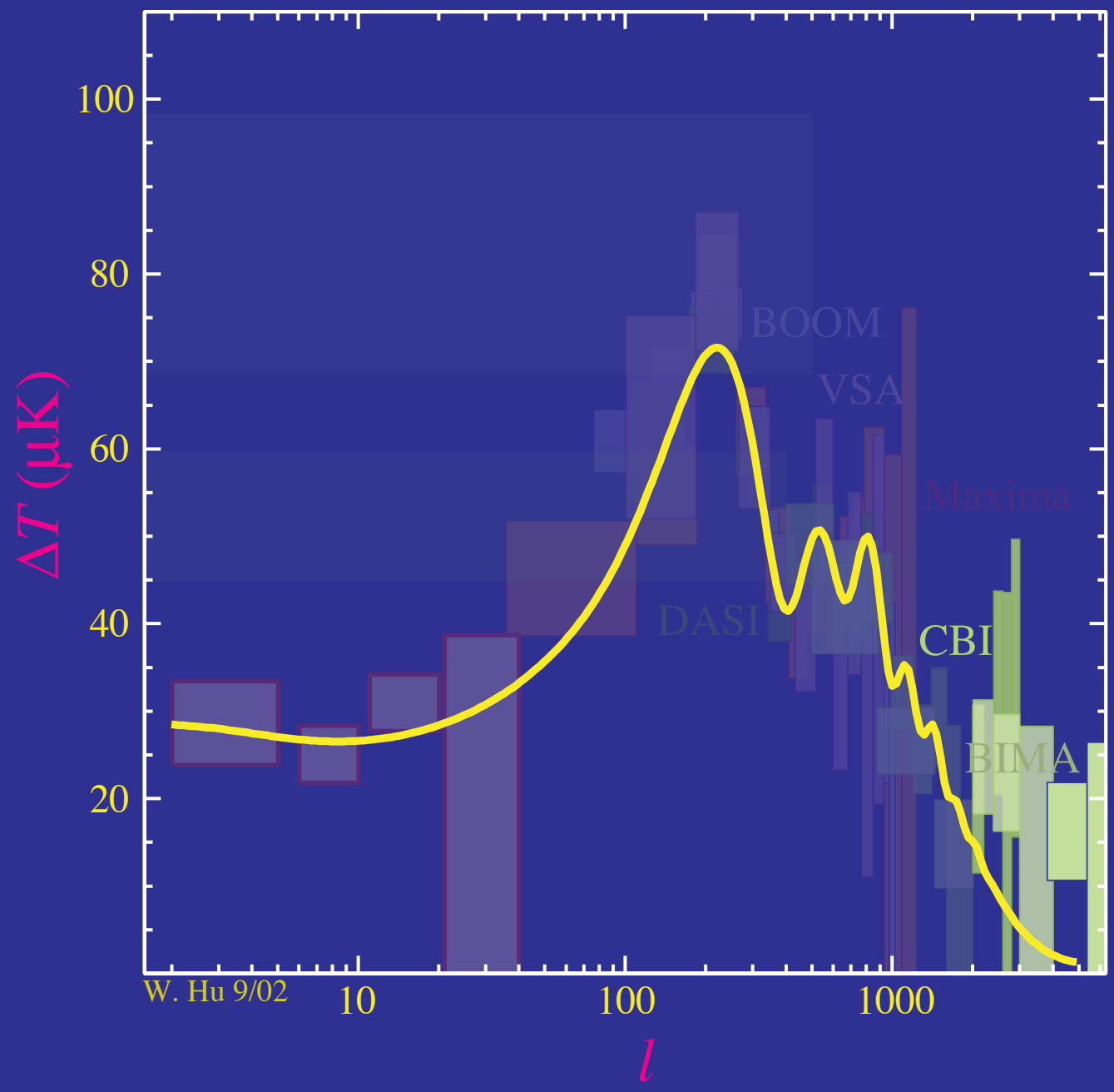
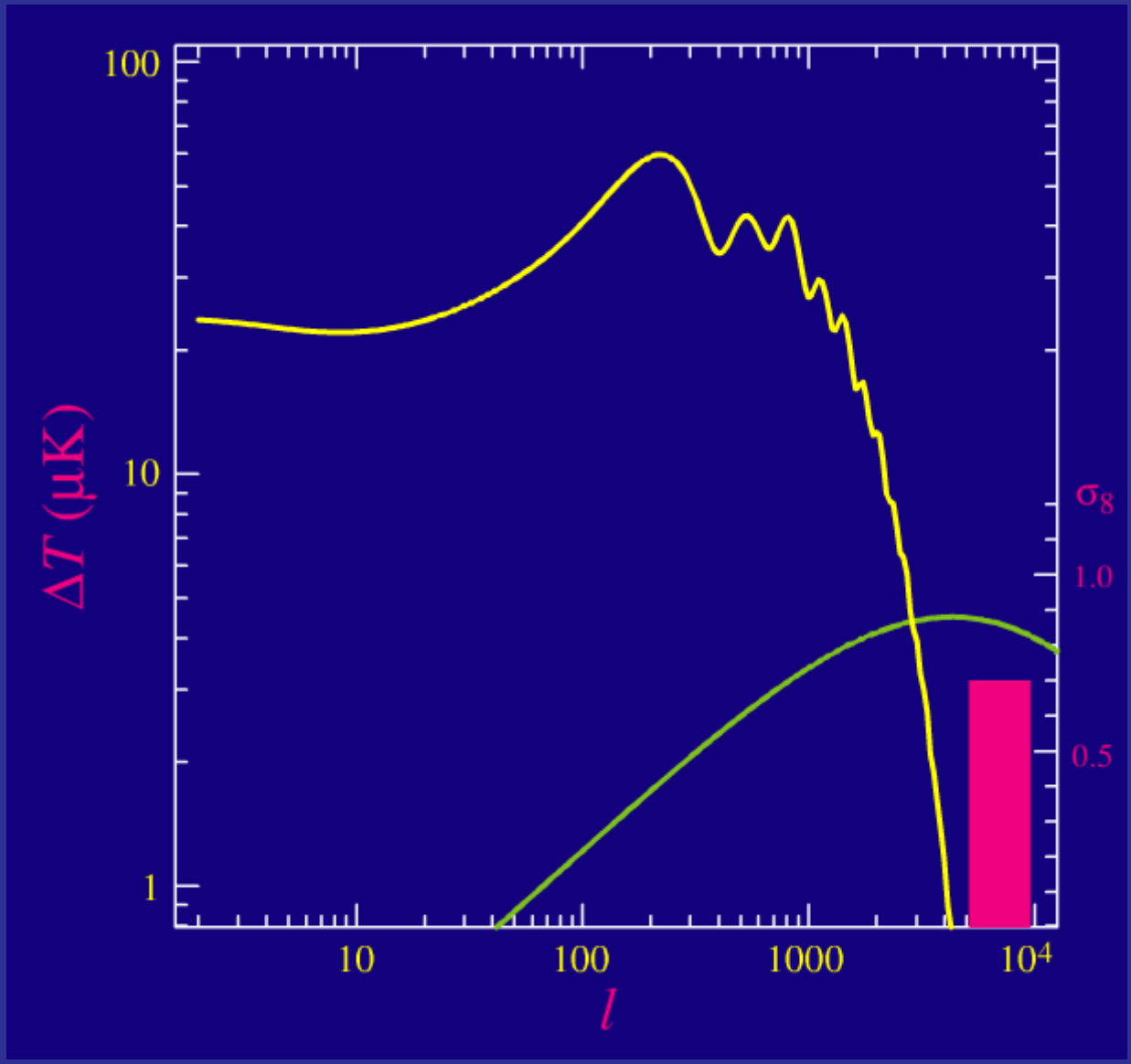
**2** Is the arcminute scale excess cosmological? SZ? reionization-$y$? or why should you care about $\sigma_8$?

# Secondary Anisotropy?



# Arcminute Excess & SZ

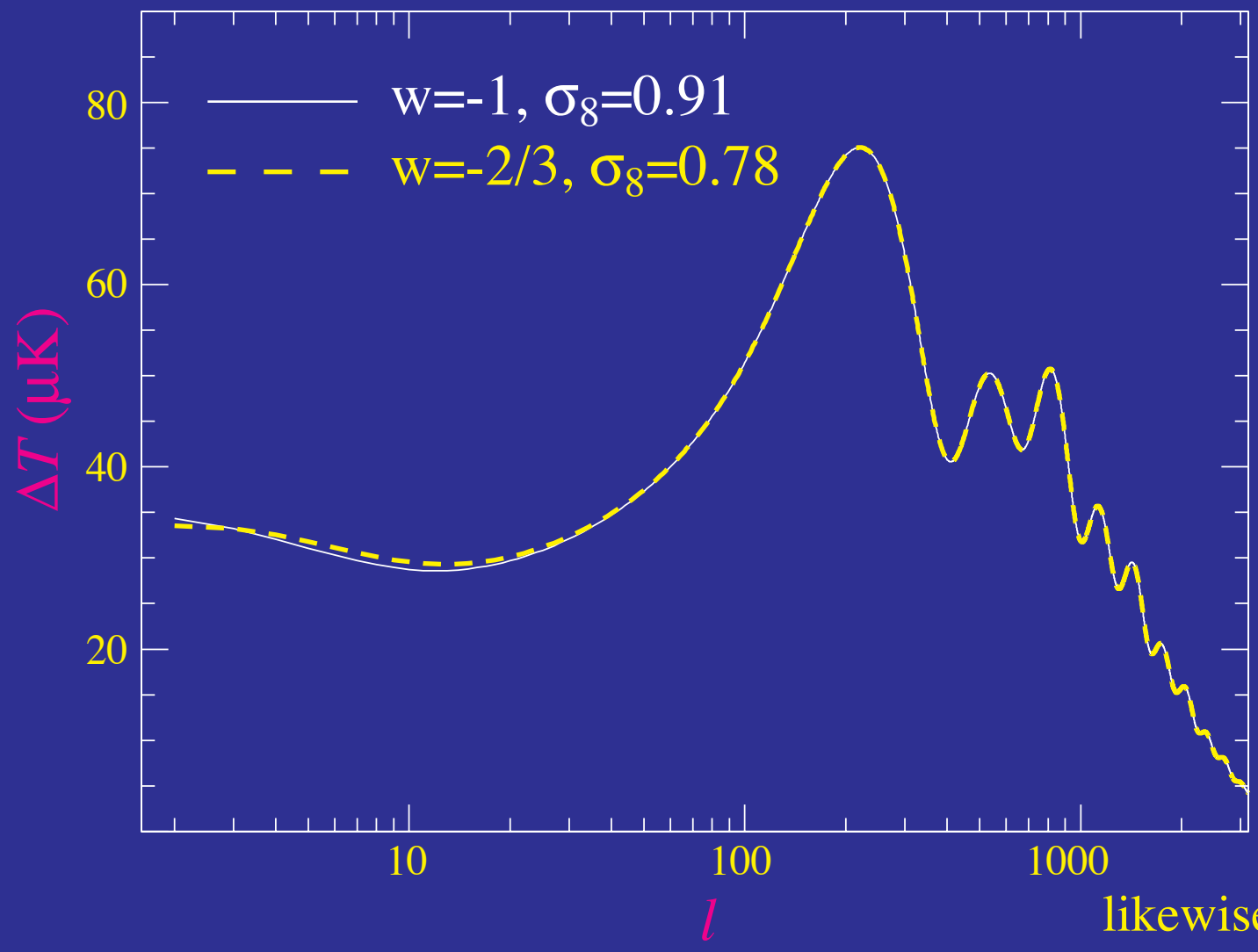
- Prediction for SZ from clusters sensitive to current amplitude as $\sigma_8^7$; with better modelling can we exploit this sensitivity?




e.g. Komatsu & Seljak (2002)

# Dark Energy and $\sigma_8$

- Angular diameter distance degeneracy broken by $\sigma_8$
  $d\ln \sigma_8 / dw = -0.43$; or $d\ln C_l^{SZ} / dw = -3$

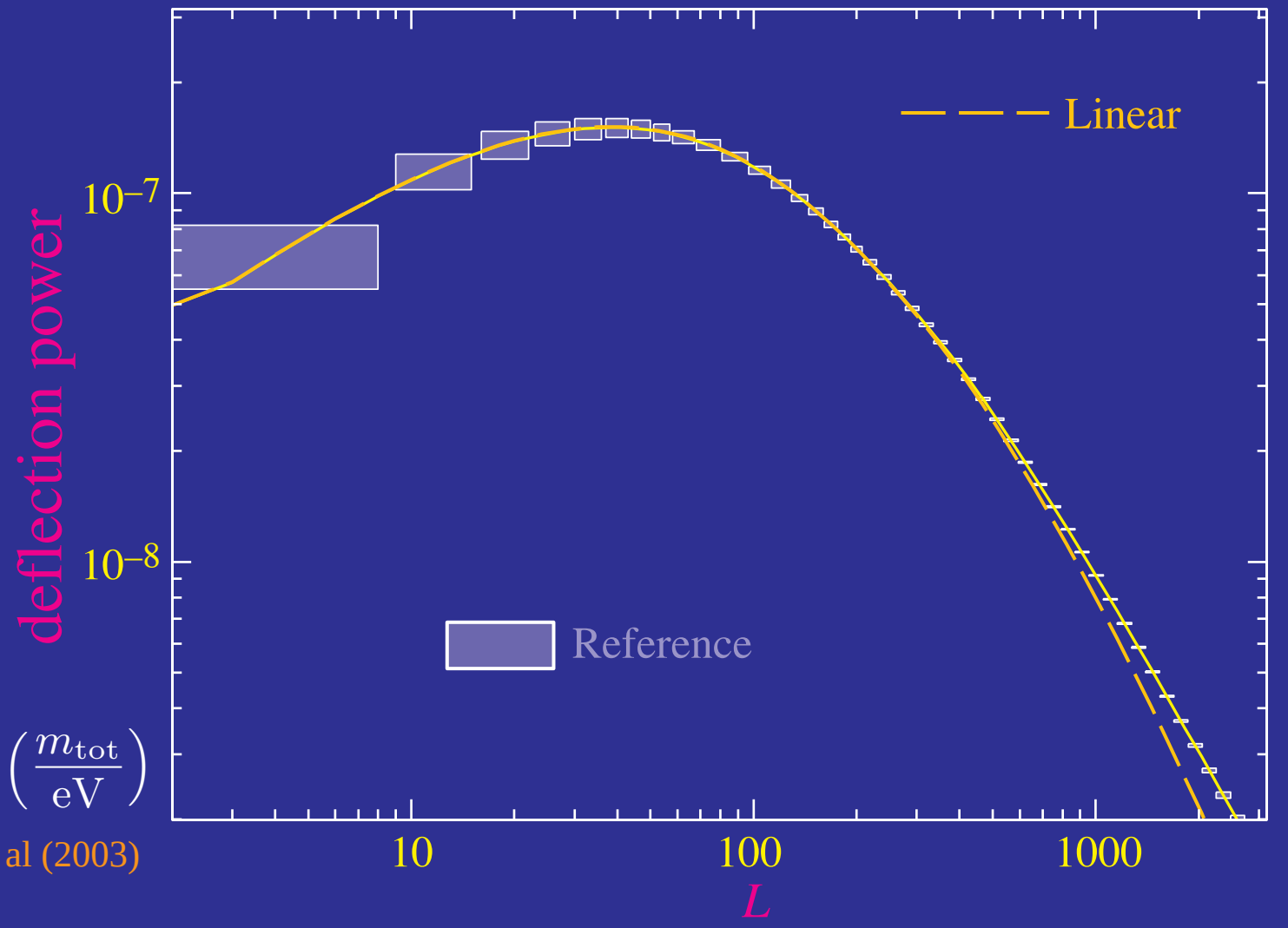



likewise neutrinos

**3** What can we learn from secondary sources of anisotropy? How will we separate their contribution? non-gaussianity? cross-correlation?

# Gravitational Lensing

- Measuring projected matter power spectrum to cosmic variance limit across whole linear regime 0.002< k < 0.2 *h*/Mpc




$$\frac{\Delta P}{P} \approx -0.6 \left(\frac{m_{\rm tot}}{\rm eV}\right)$$

Kaplinghat et al (2003)

avoids reionization ambiguity combine with lower z for dark energy

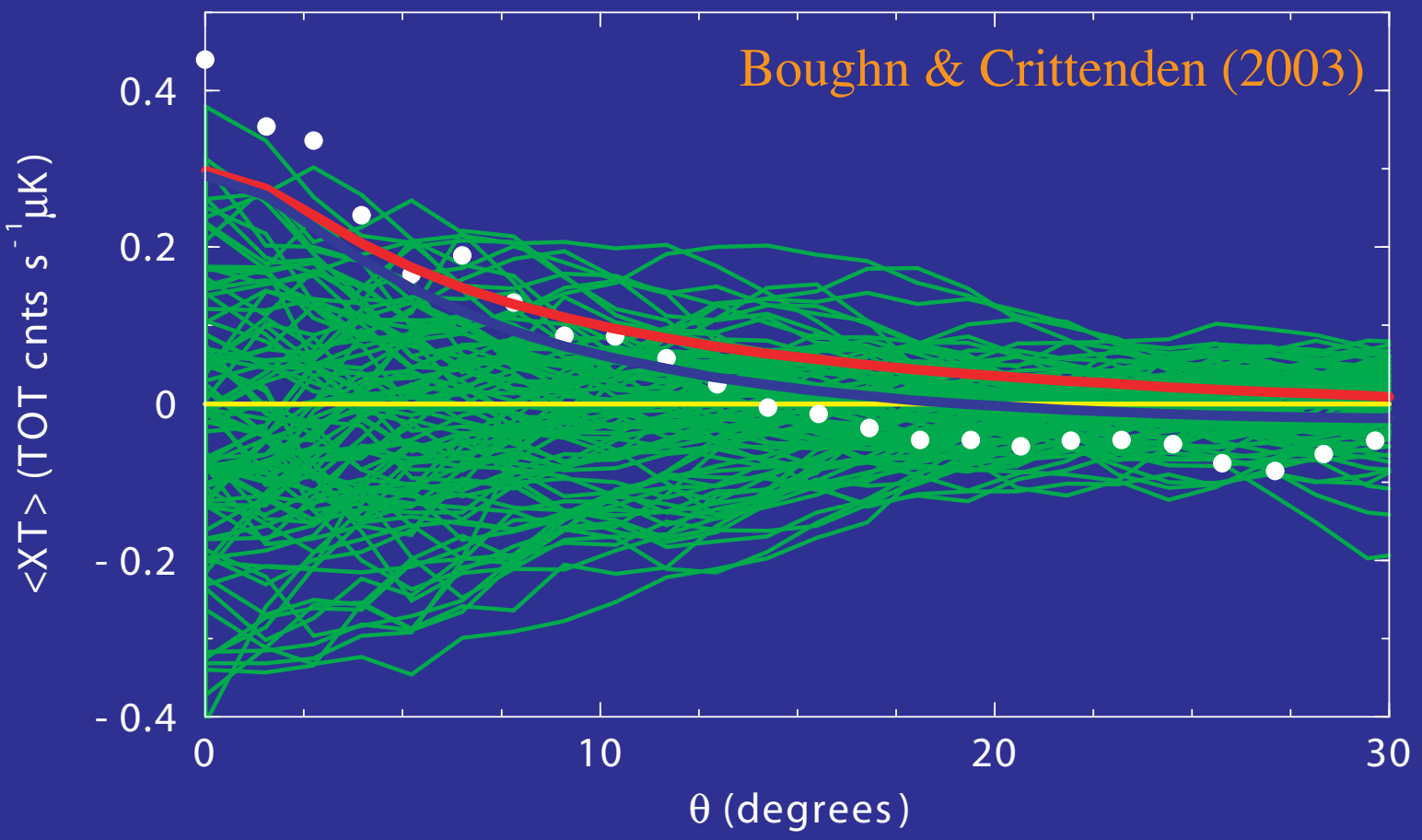
Hu & Okamoto (2001); Hirata & Seljak (2002; 2003)

$\sigma(w)$~0.06

**4** What more can we learn about the dark energy? what are the future prospects for ISW-galaxy correlation studies

# ISW Galaxy Correlation

- Supporting evidence for dark energy (specifically a "smooth" component, affects Friedmann but not Poisson, including curvature)

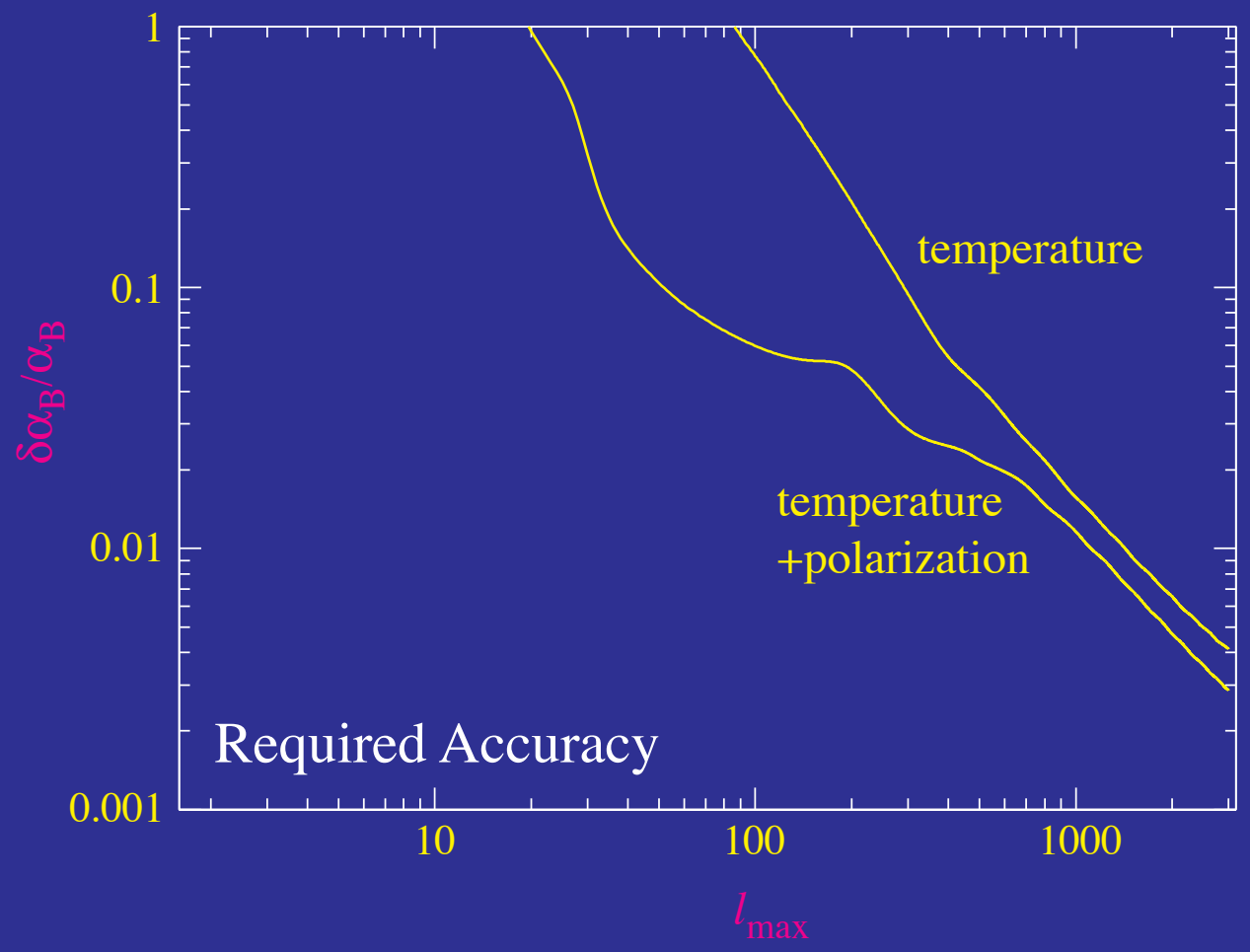



Boughn & Crittenden (2003); Nolte et al (2003); Fosalba & Gaztanaga (2003); Fosalba et al (2003); Afshordi et al (2003)

**5** Precision or accuracy? do we understand recombination sufficiently well?

# Recombination

- RECFast mocks up a multilevel atom with a fudge to case B: 1.14, causes systematic error in predictions larger than numerics at $l$>1000




RECFAST: Seager et al. (1999)

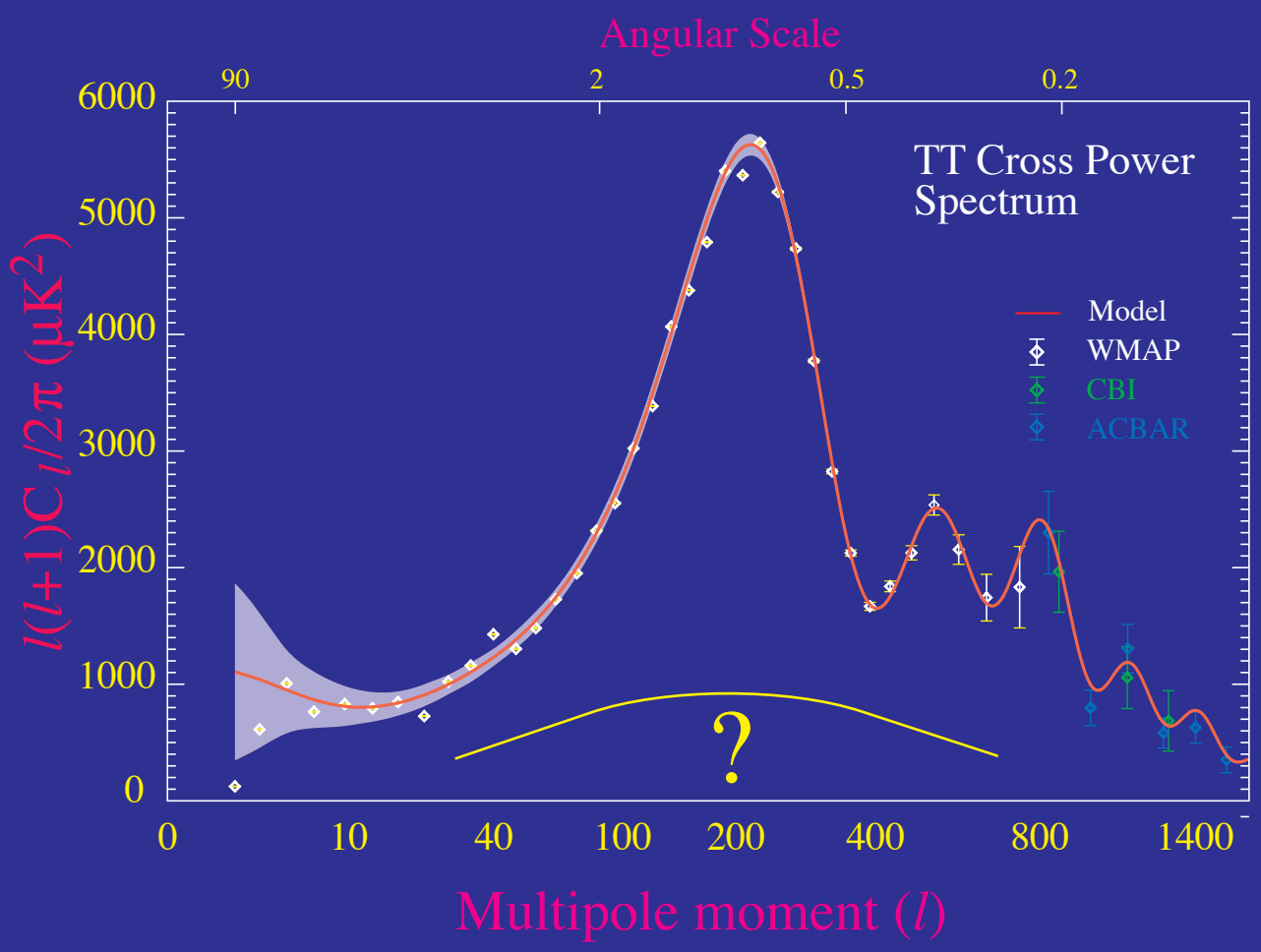
**6** Is there any CMB-only evidence for a running of the tilt?

what are the prospects for precision (and accurate!)

initial conditions studies in the future?

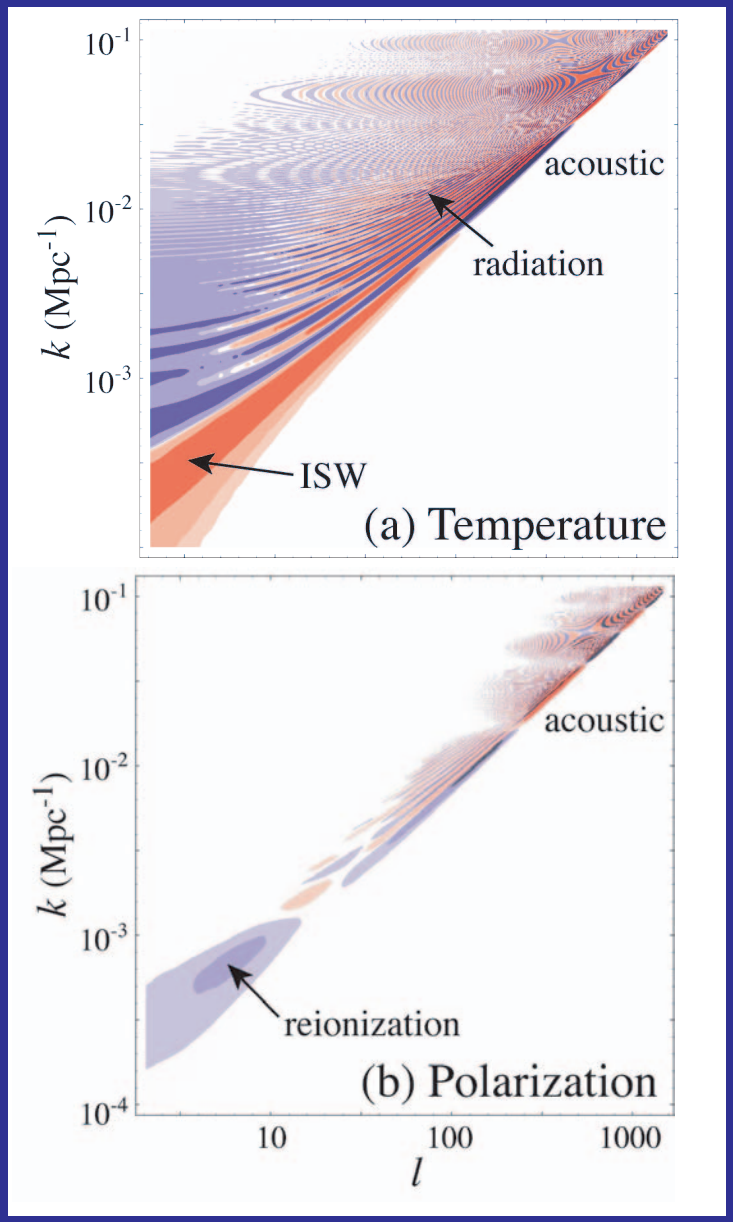
# Running?

- Combining WMAP (including low l anomalies) with damping tail...




WMAP: Bennett et al (2003)

# Transfer of Initial Power

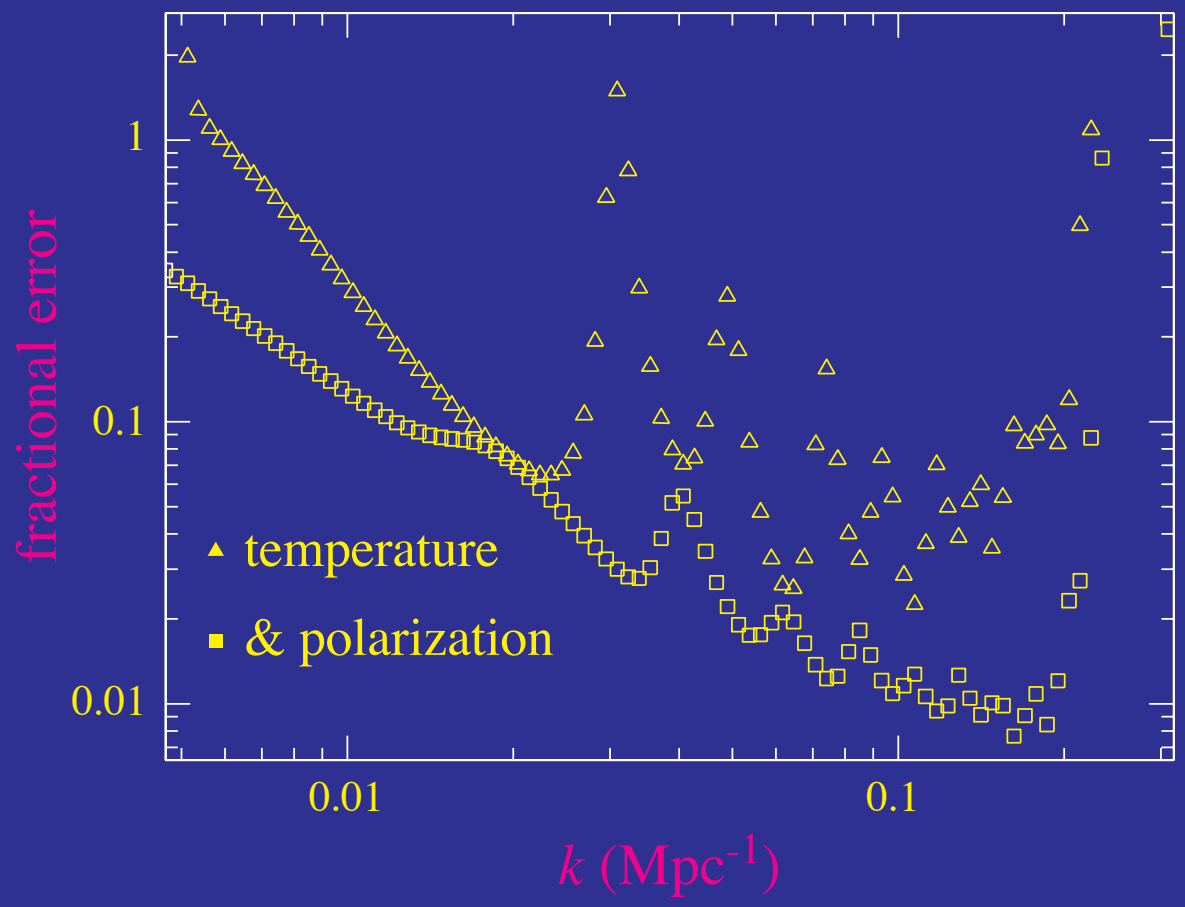



Hu & Okamoto (2003)

# Prospects for Initial Conditions

- Polarization crucial for detailed study of initial conditions, decade in scale of the acoustic peaks can provide exquisite tests of scale free initial conditions

Hu & Okamoto (2003)




cosmological parameters fixed

even with large lever arm other tests must match accuracy

Wang et al (1999); Kinney (2001); Miller et al (2002); Tegmark & Zaldarriaga (2002); Bridle et al (2003)

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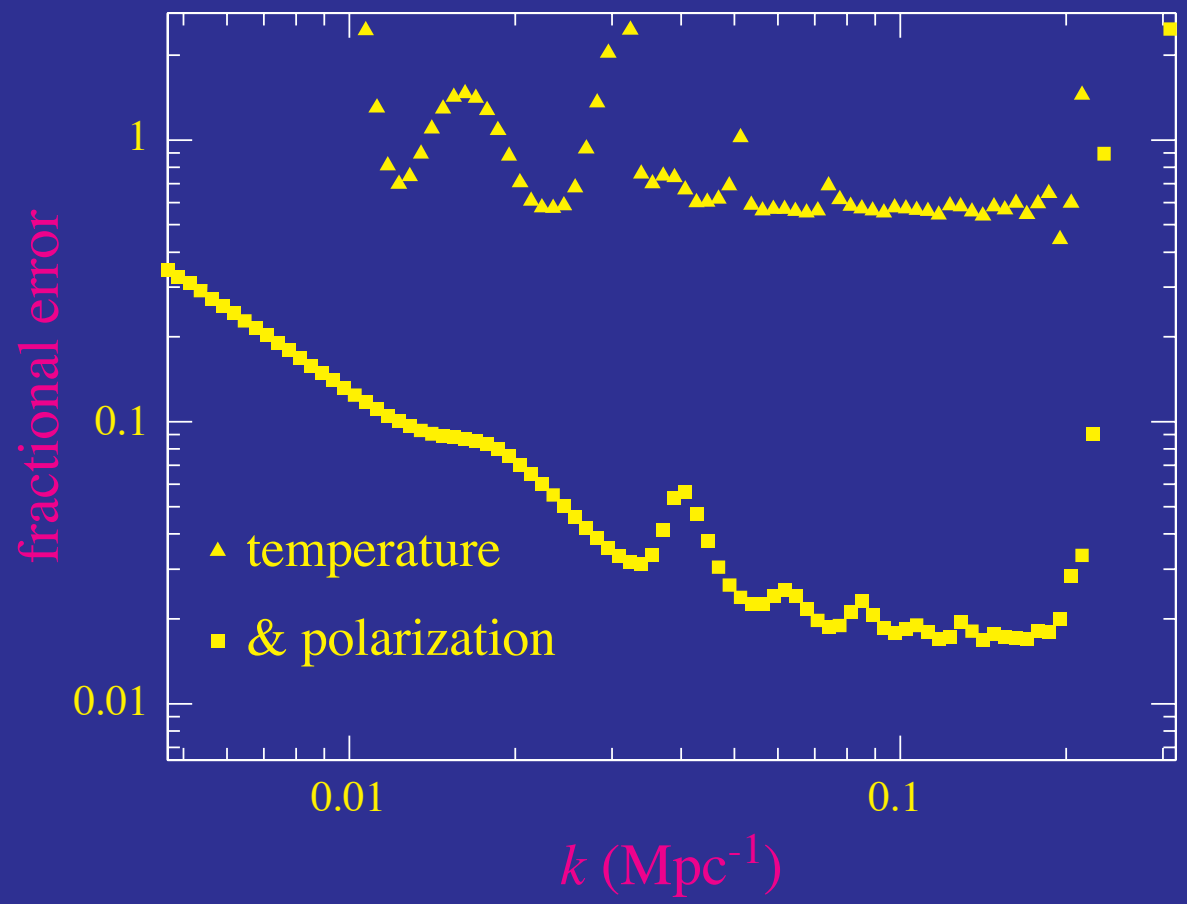


cosmological parameters marginalized

even with large lever arm other tests must match accuracy

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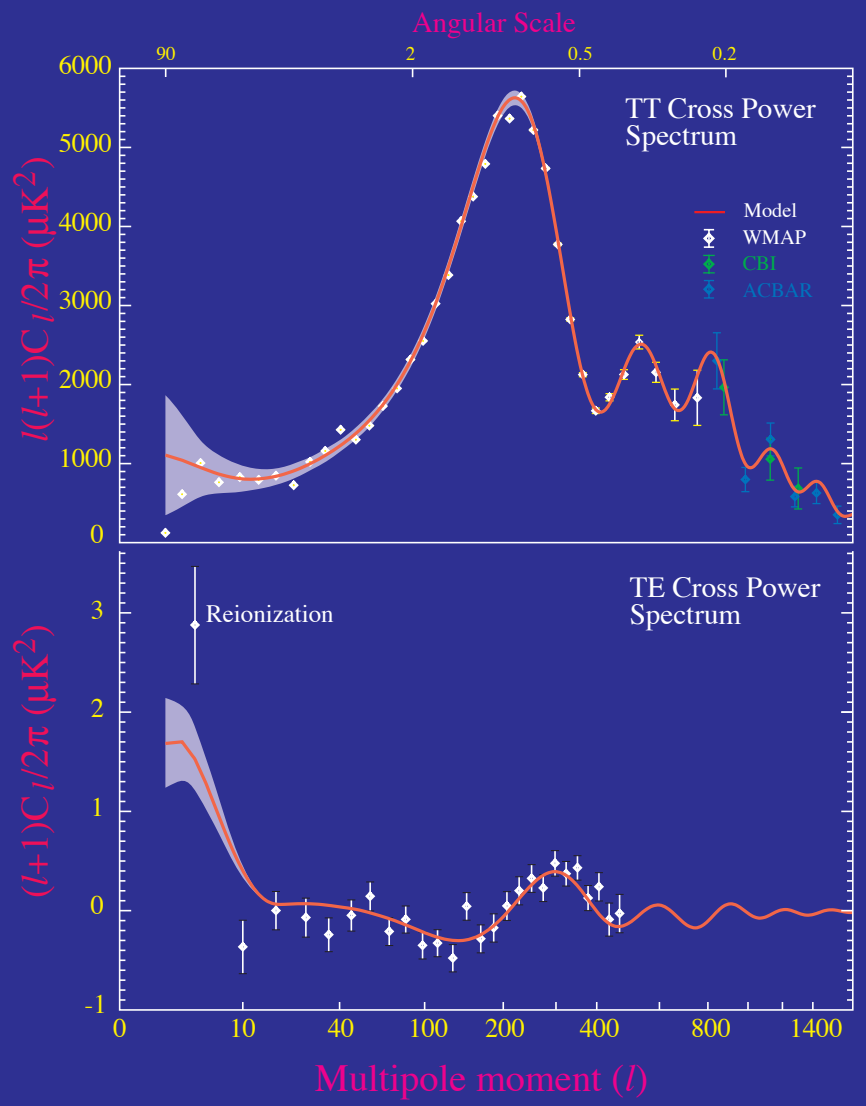
**7** Are the low multipole anomalies signifcant? if so what do they imply for cosmology (topology, dark energy, ...) and/or foreground contamination

# Low *l* Anomalies

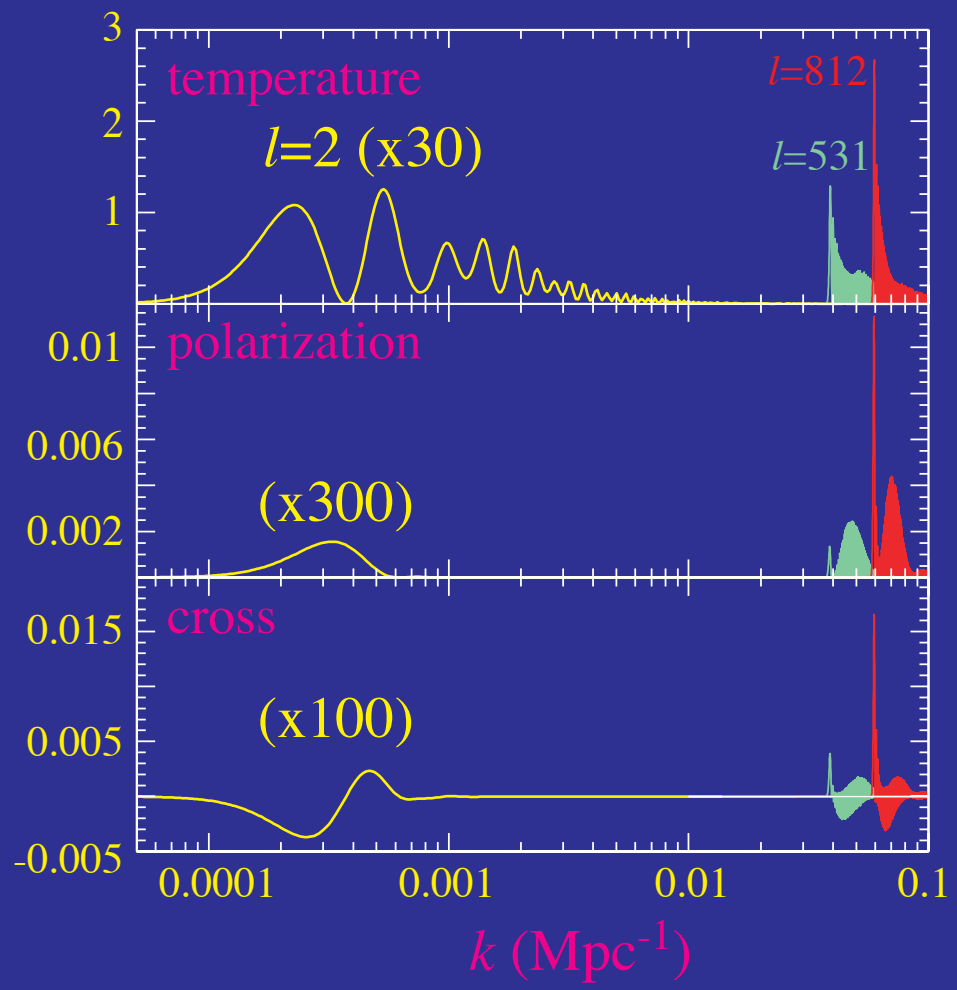
- Low quadrupole, octupole; C(θ); alignment; hemispheres; TT vs TE




e.g. COBE; Bennett et al (2003); Tegmark et al (2003); Efstathiou (2003); Erickson et al (2003); Dore et al (2003); Park (2003)

# Sharper Probe of Large Scales?

- Polarization reionization bump arises from a tight range of scales at high-z; separate explanations due to primordial power and dark energy




Hu & Okamoto (2003)

# Questions, Questions...

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**5** Precision or accuracy? do we understand reionization sufficiently?

**6** Evidence for a running of the tilt? what are the prospects for precision (and accurate!) initial conditions studies in the future?

**7** Are the low multipole anomalies signifcant? coincidence? topology? dark energy? foregrounds?