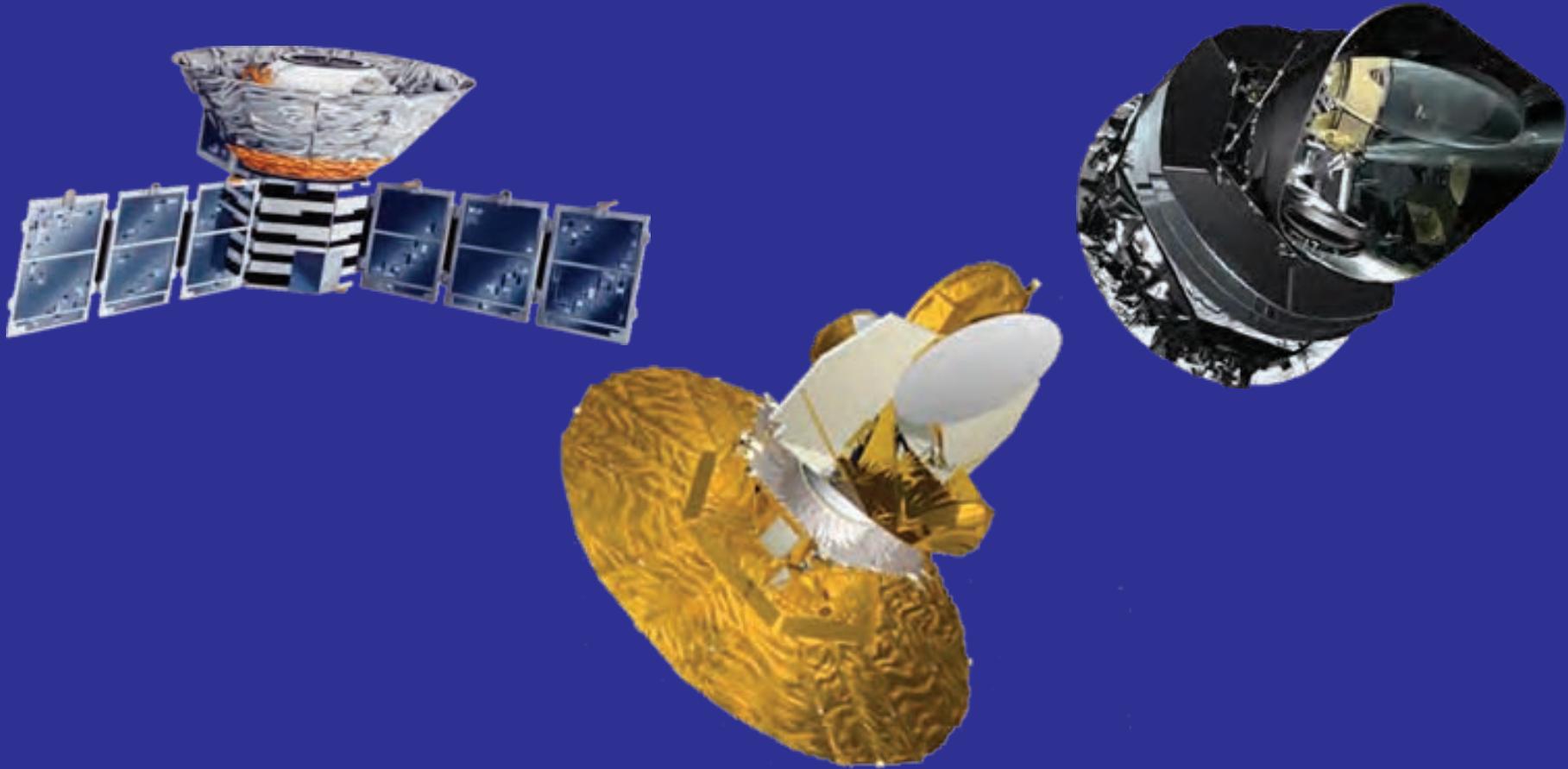


# Ghosts of CMB



Past, Present & Future

*Wayne Hu*

Avignon, April 2008

# Milestones: Past & Present

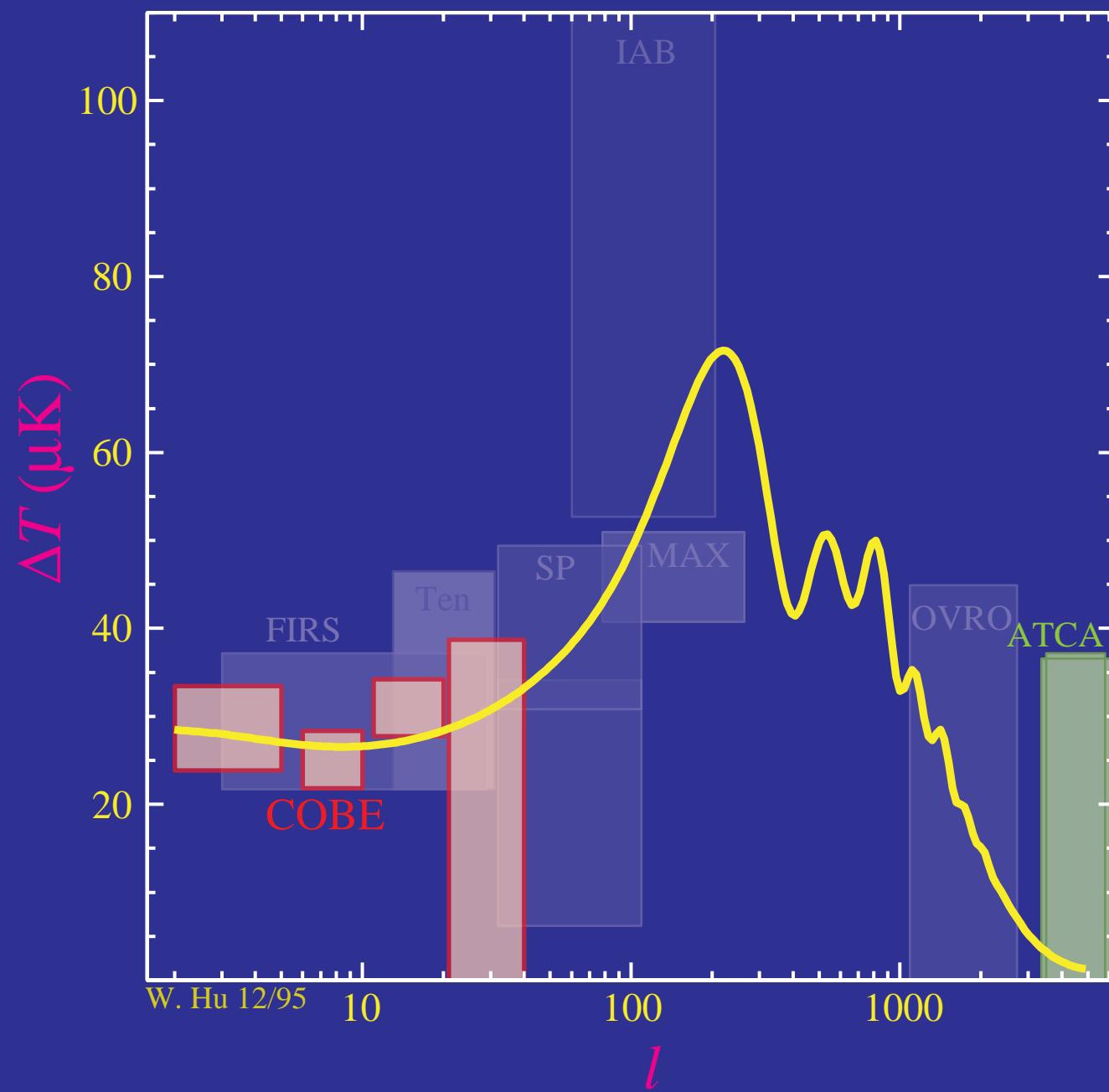
|                                    |                    |         |
|------------------------------------|--------------------|---------|
| • Large-scale anisotropy           | COBE DMR           | '92     |
| • Degree-scale anisotropy          | many               | '93-'99 |
| • First acoustic peak              | Toco, Boom, Maxima | '99-'00 |
| • Secondary acoustic peak(s)       | DASI, Boom         | '01     |
| • Damping tail                     | CBI                | '02     |
| • Acoustic polarization            | DASI               | '02     |
| • Secondary anisotropy?            | CBI                | '02     |
| • Reionization                     | WMAP               | '03     |
| • ISW correlation                  | WMAP+LSS           | '03     |
| • Large scale anomalies?           | WMAP (COBE)        | '03     |
| • Tilt (or finite slow roll param) | WMAP(+ext, LSS)    | '06     |
| • Lensing correlation              | WMAP+LSS           | '07     |
| • Primordial non-Gaussianity?      | WMAP               | '07     |
| • Lensing smoothing                | ACBAR              | '08     |

# Milestones: Future

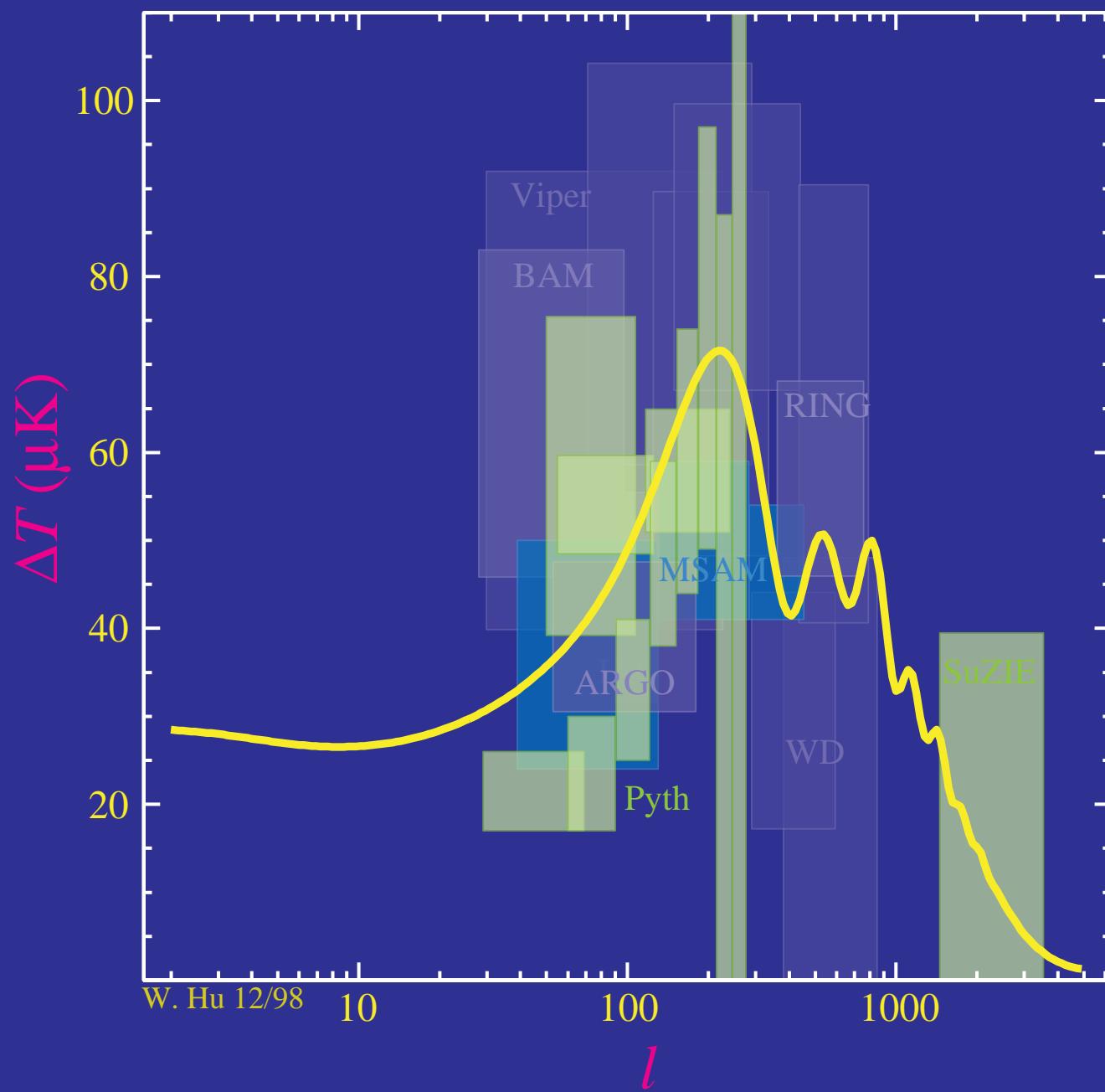
- Sunyaev-Zel'dovich cluster & secondaries surveys
- Polarization tests of large-scale temperature anomalies
- Lensing B-modes
- Lensing mass reconstruction
- Reionization history & inhomogeneity
- Gravitational wave B-modes

# Past: Establishing the Standard Model

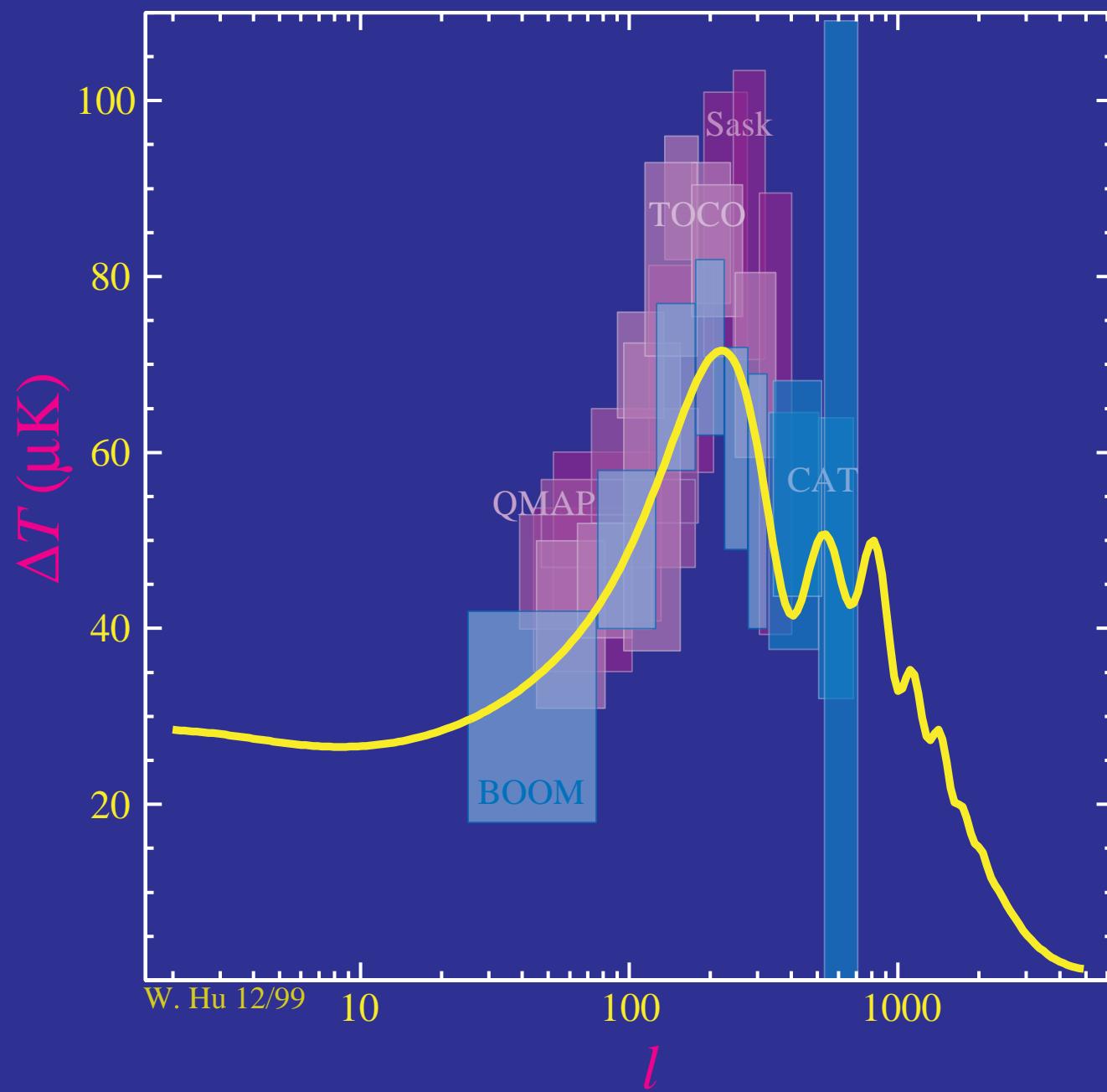
# Power Spectrum Past



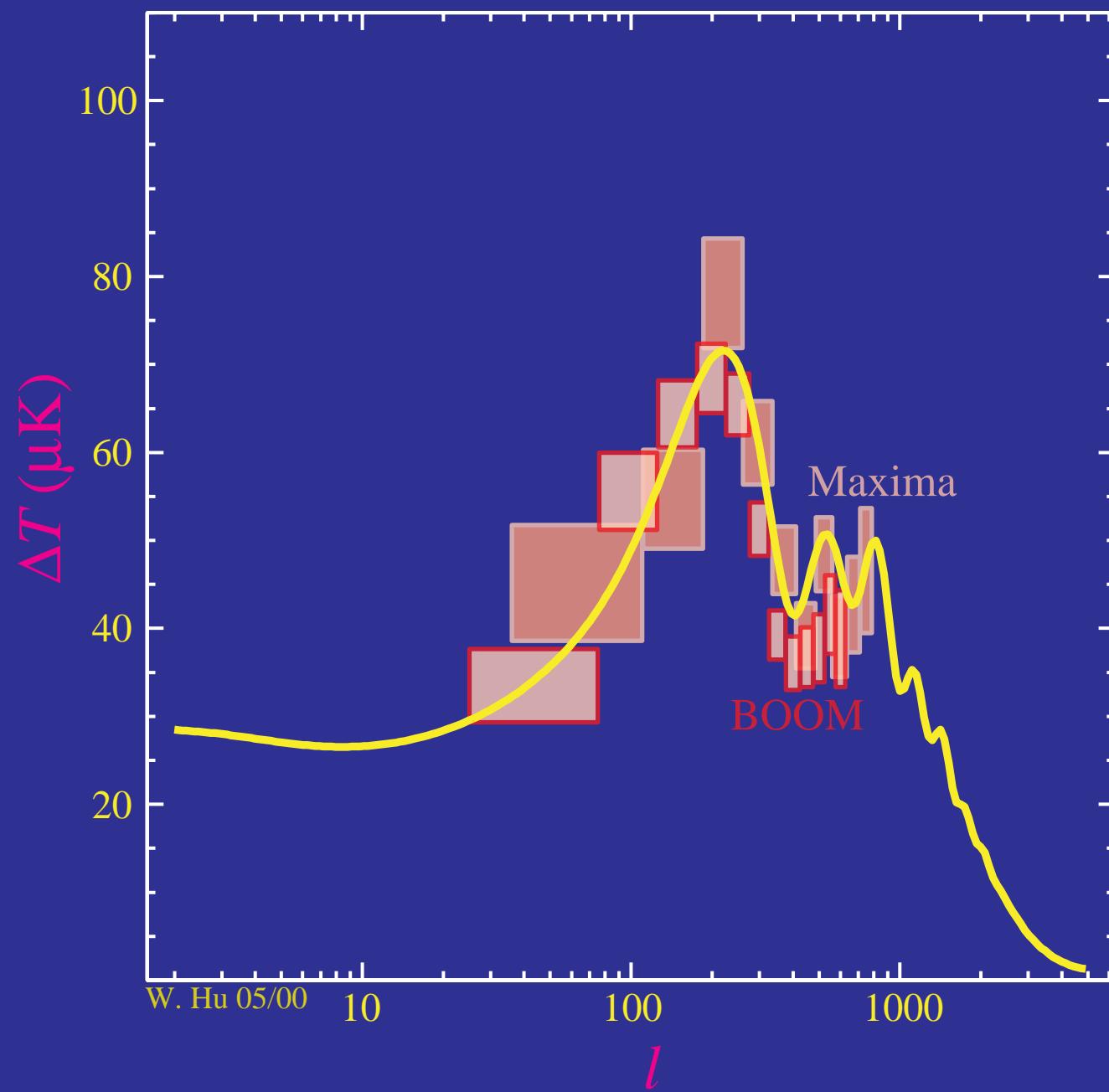
# Power Spectrum Past



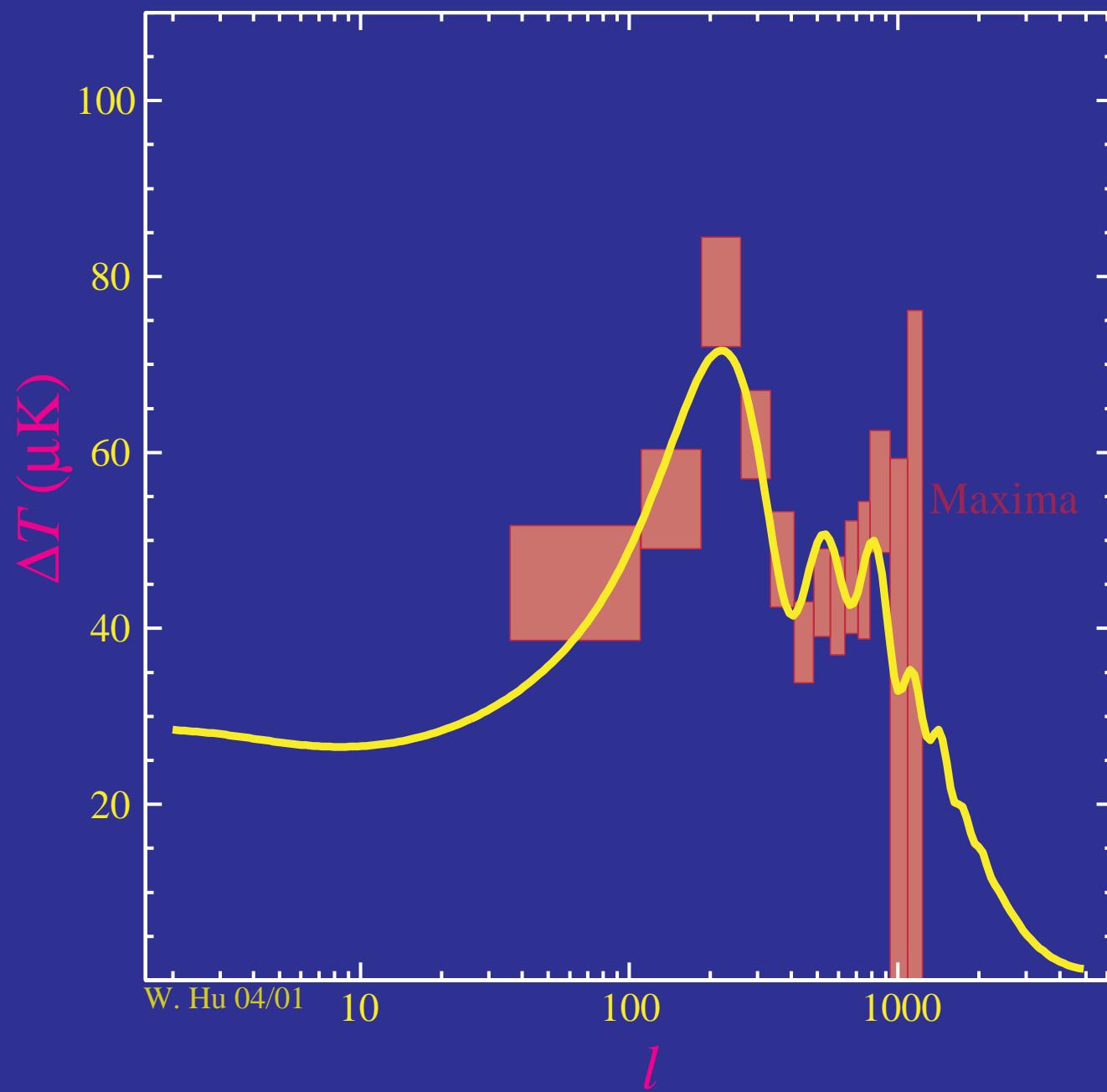
# Power Spectrum Past



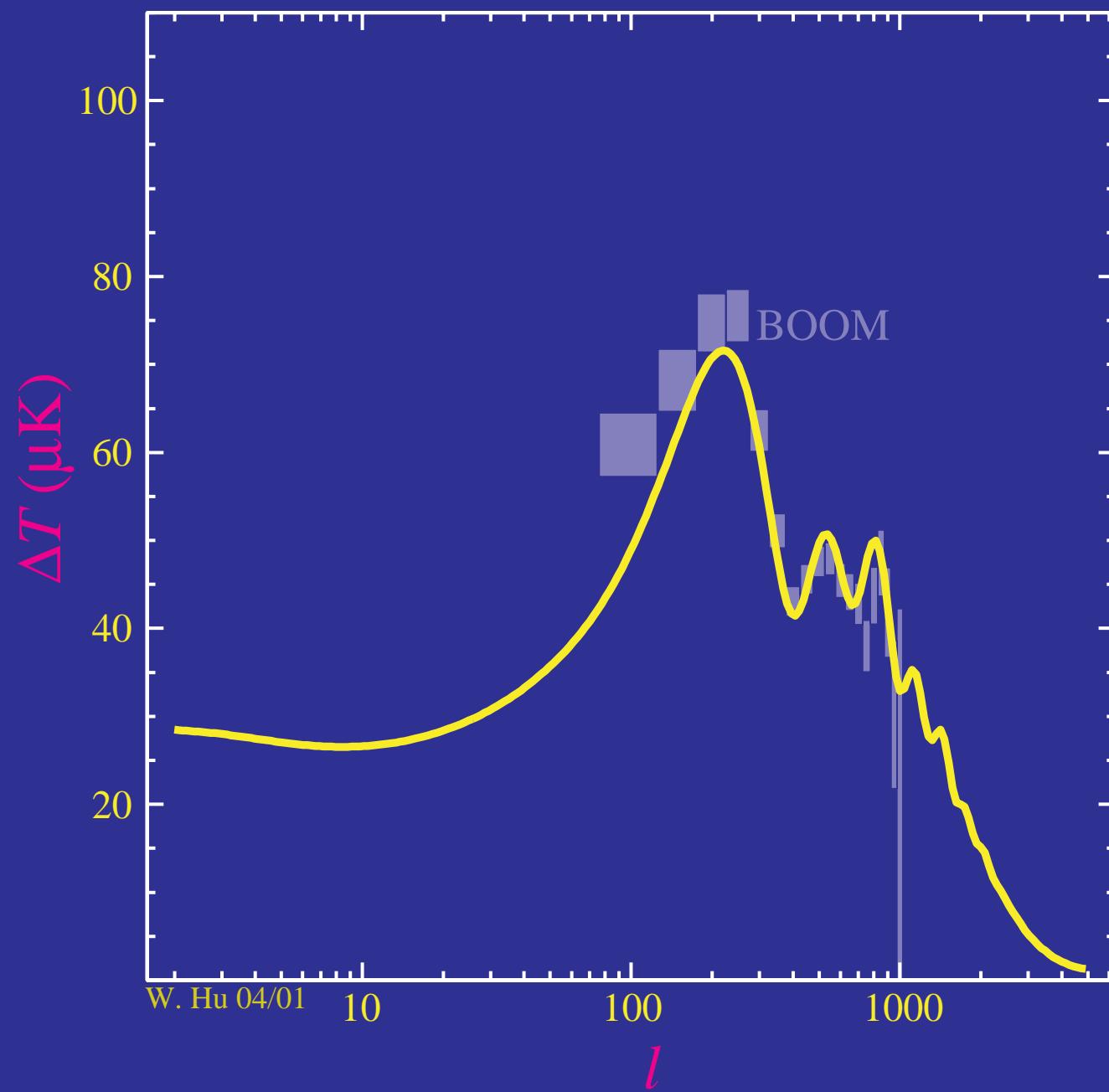
# Power Spectrum Past



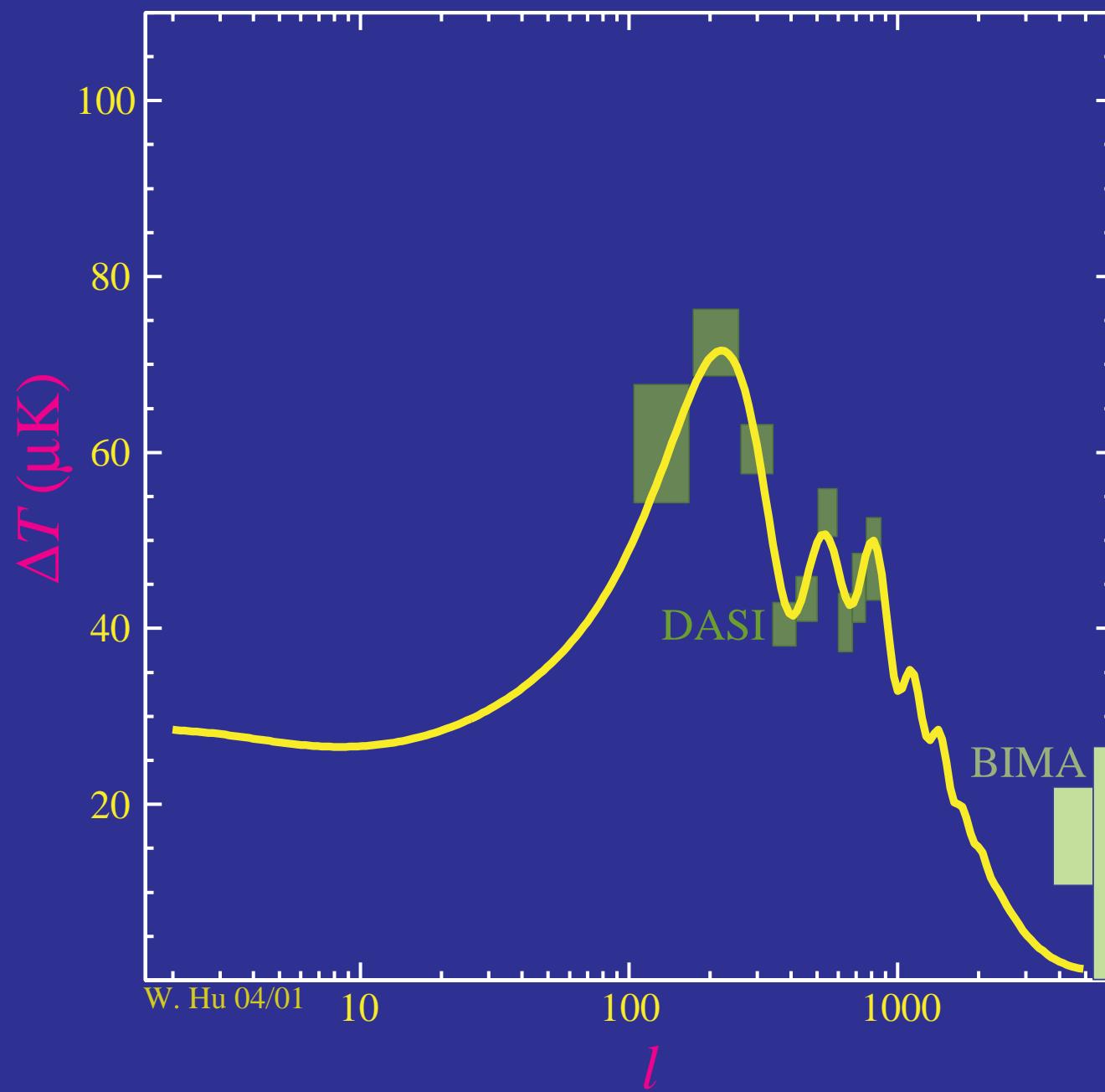
# Power Spectrum Past



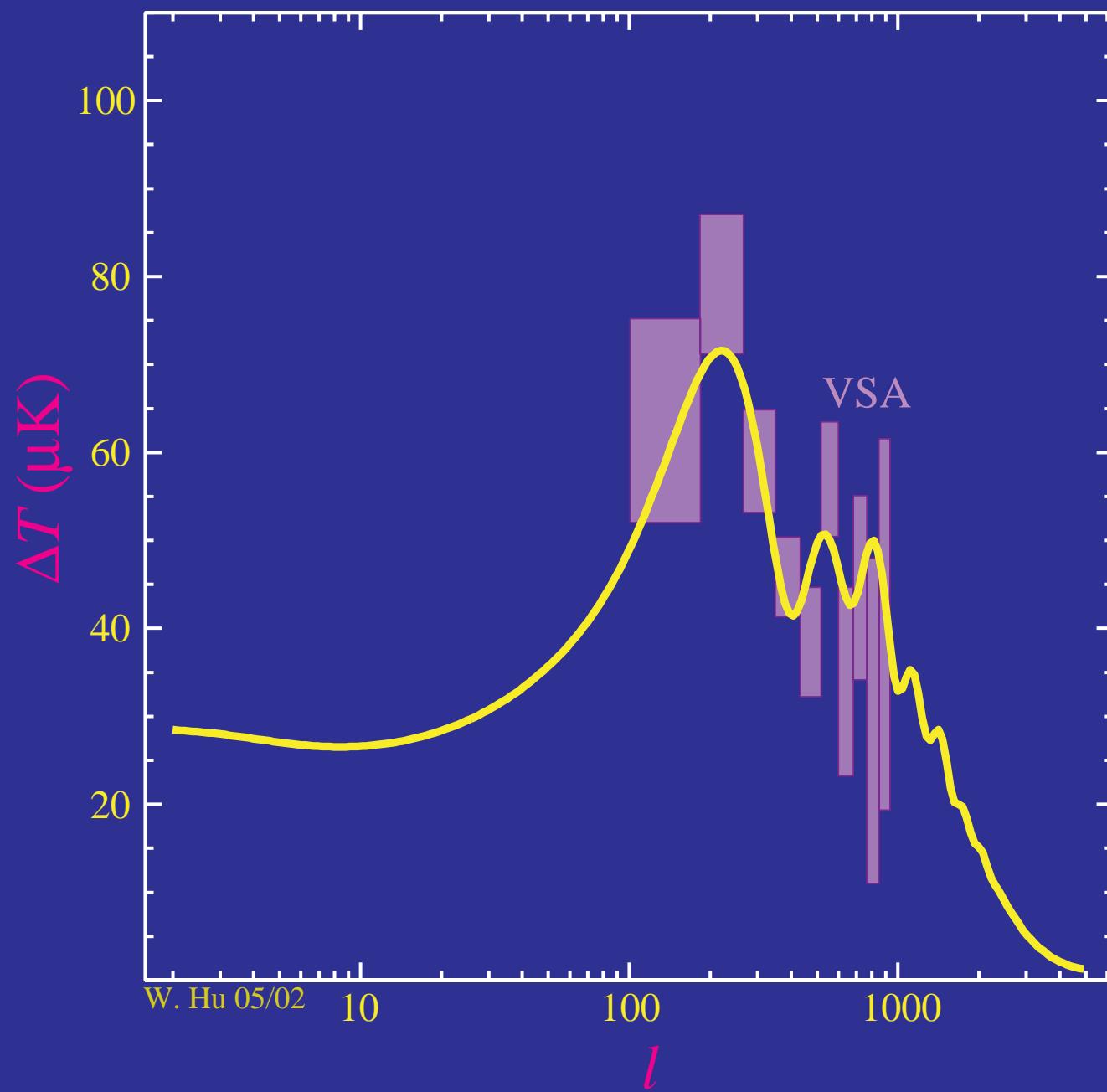
# Power Spectrum Past



# Power Spectrum Past

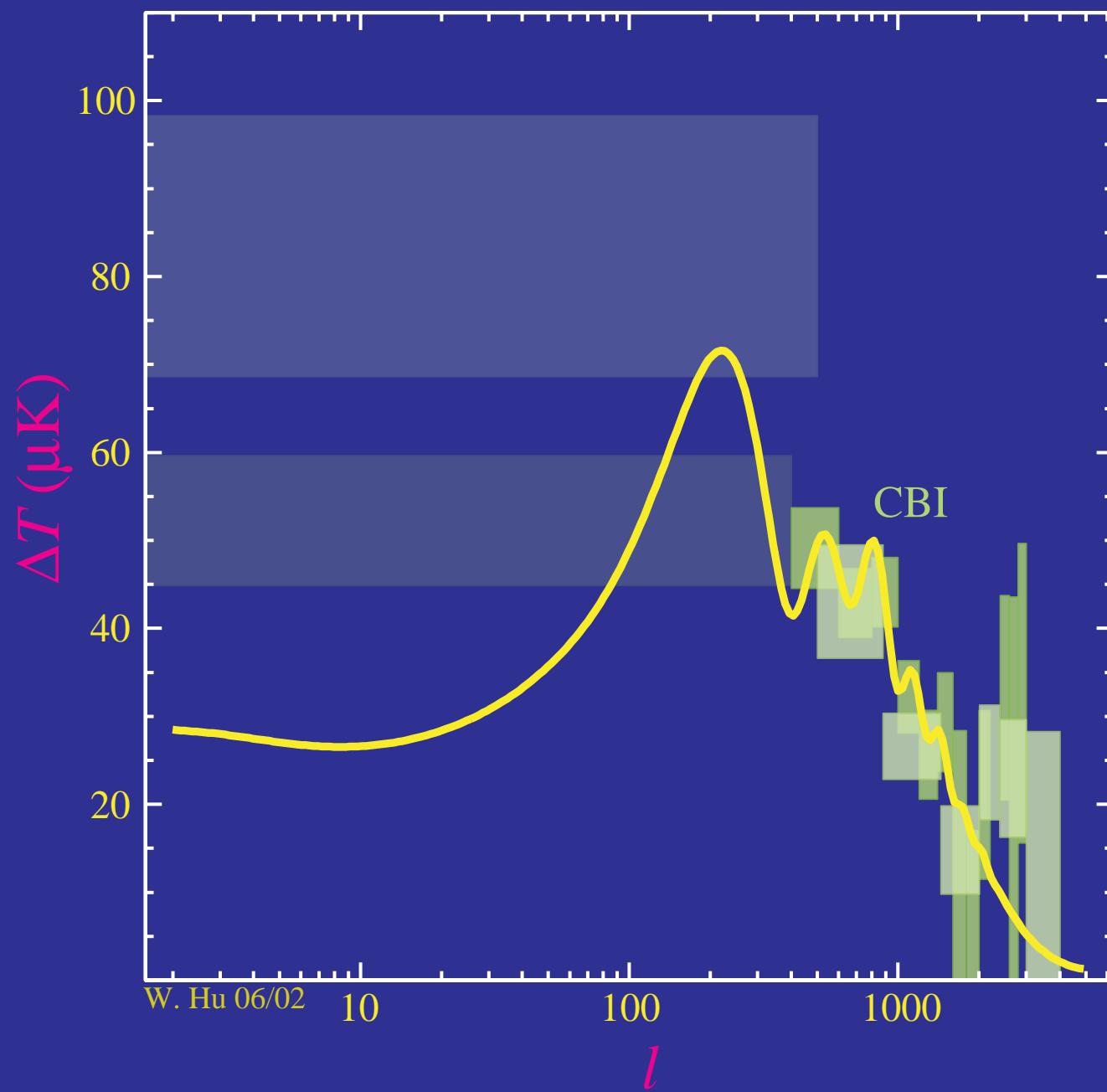


# Power Spectrum Past

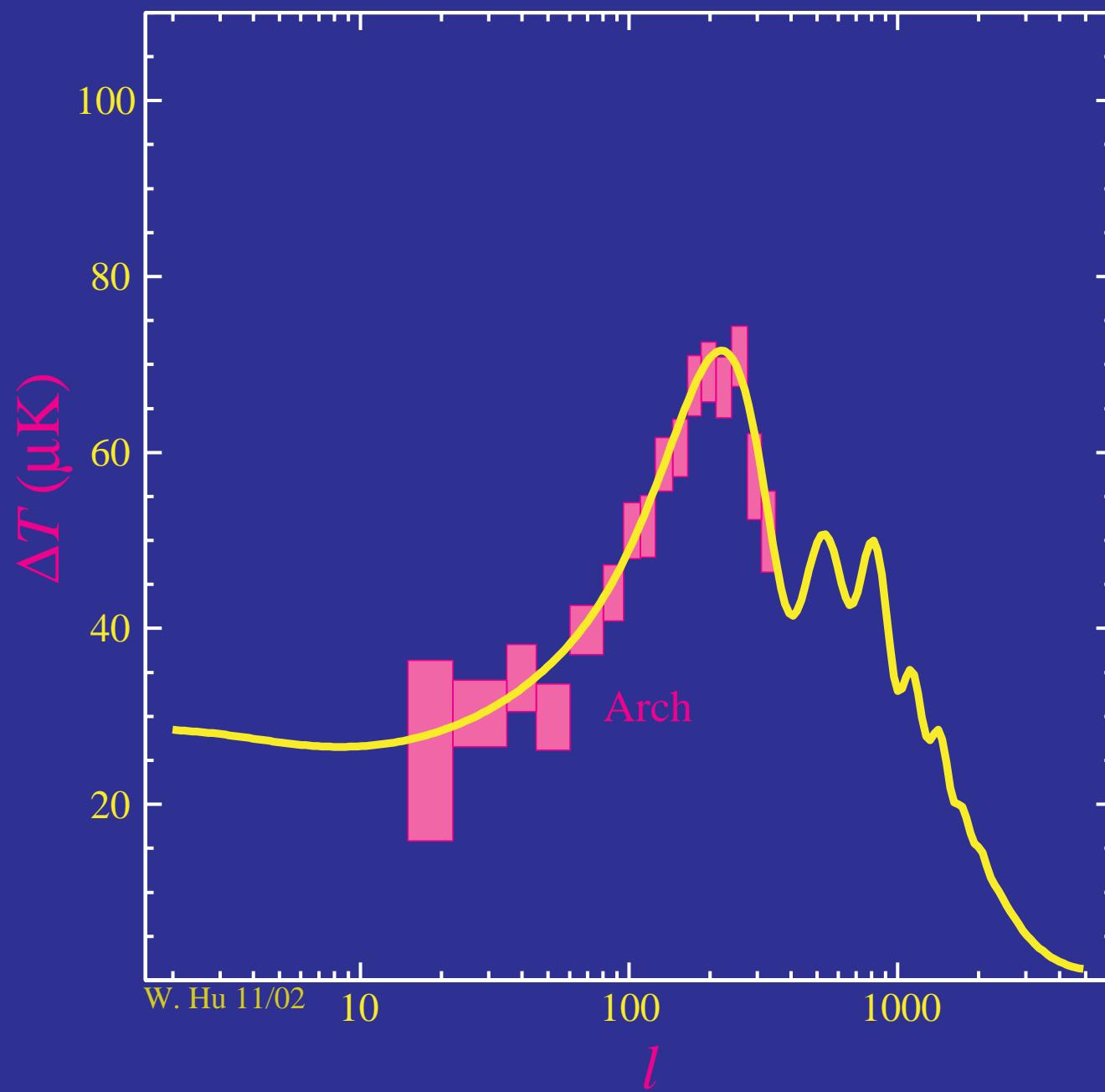


W. Hu 05/02

# Power Spectrum Past

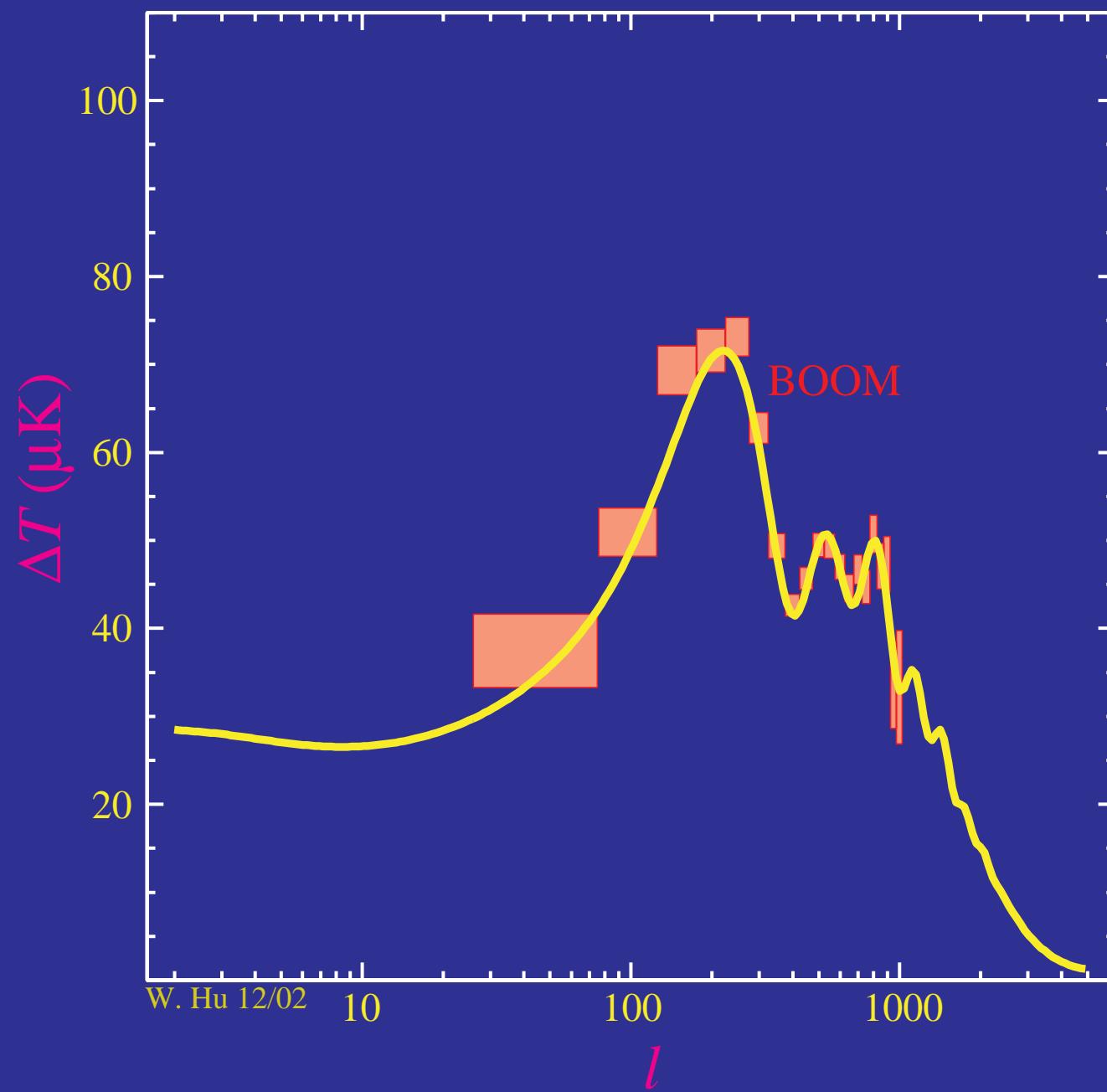


# Power Spectrum Past

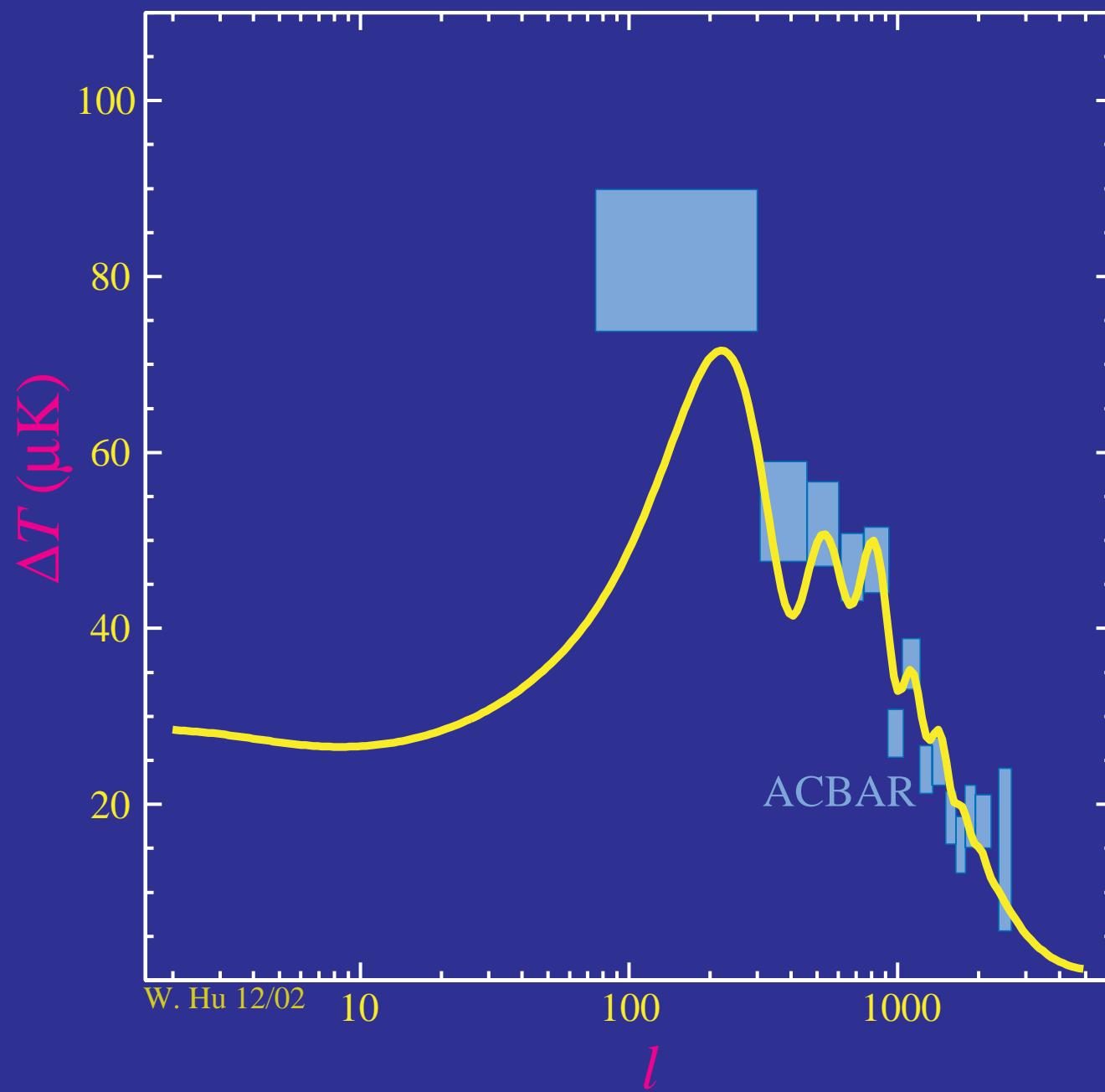


W. Hu 11/02

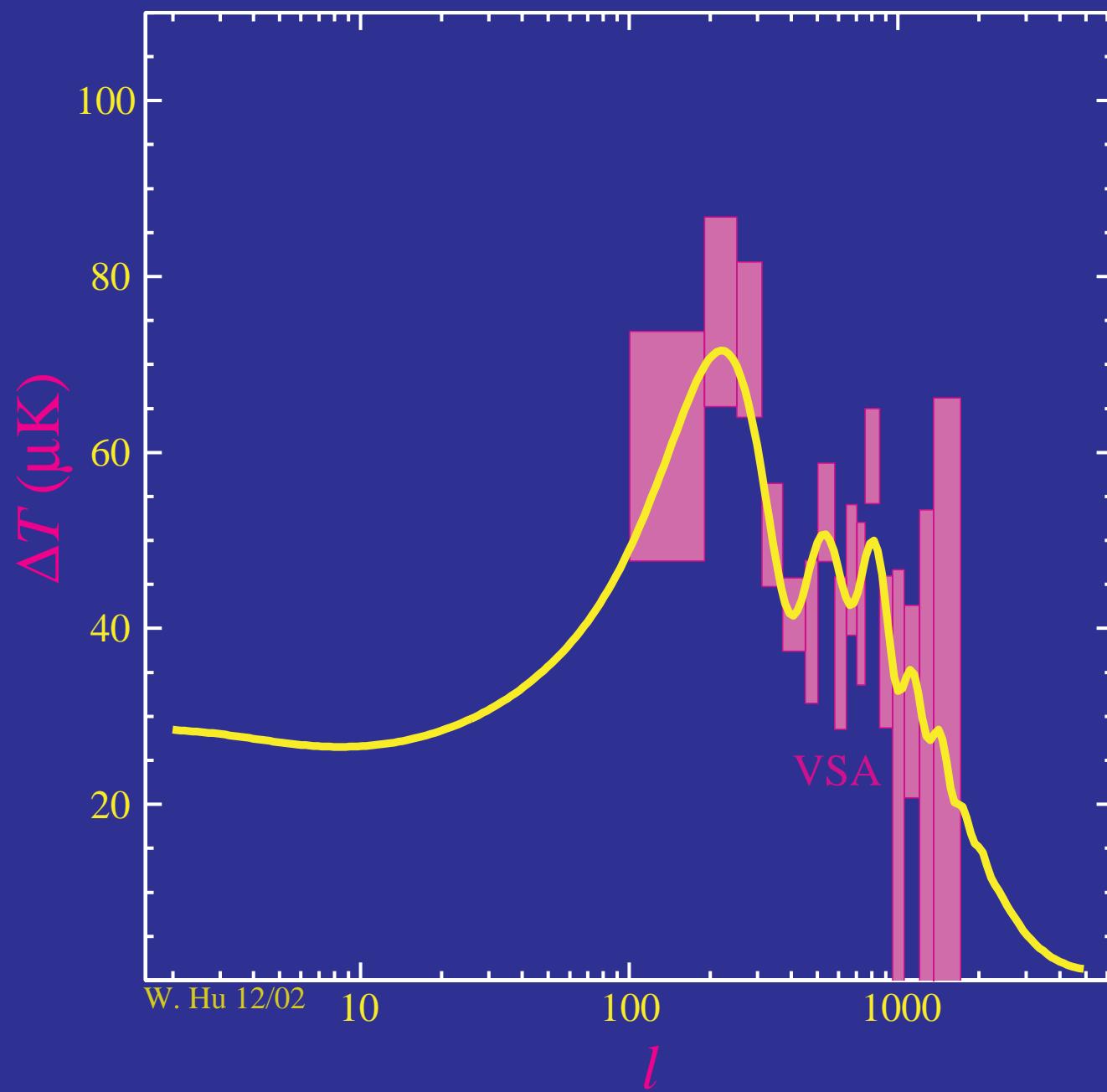
# Power Spectrum Past



# Power Spectrum Past



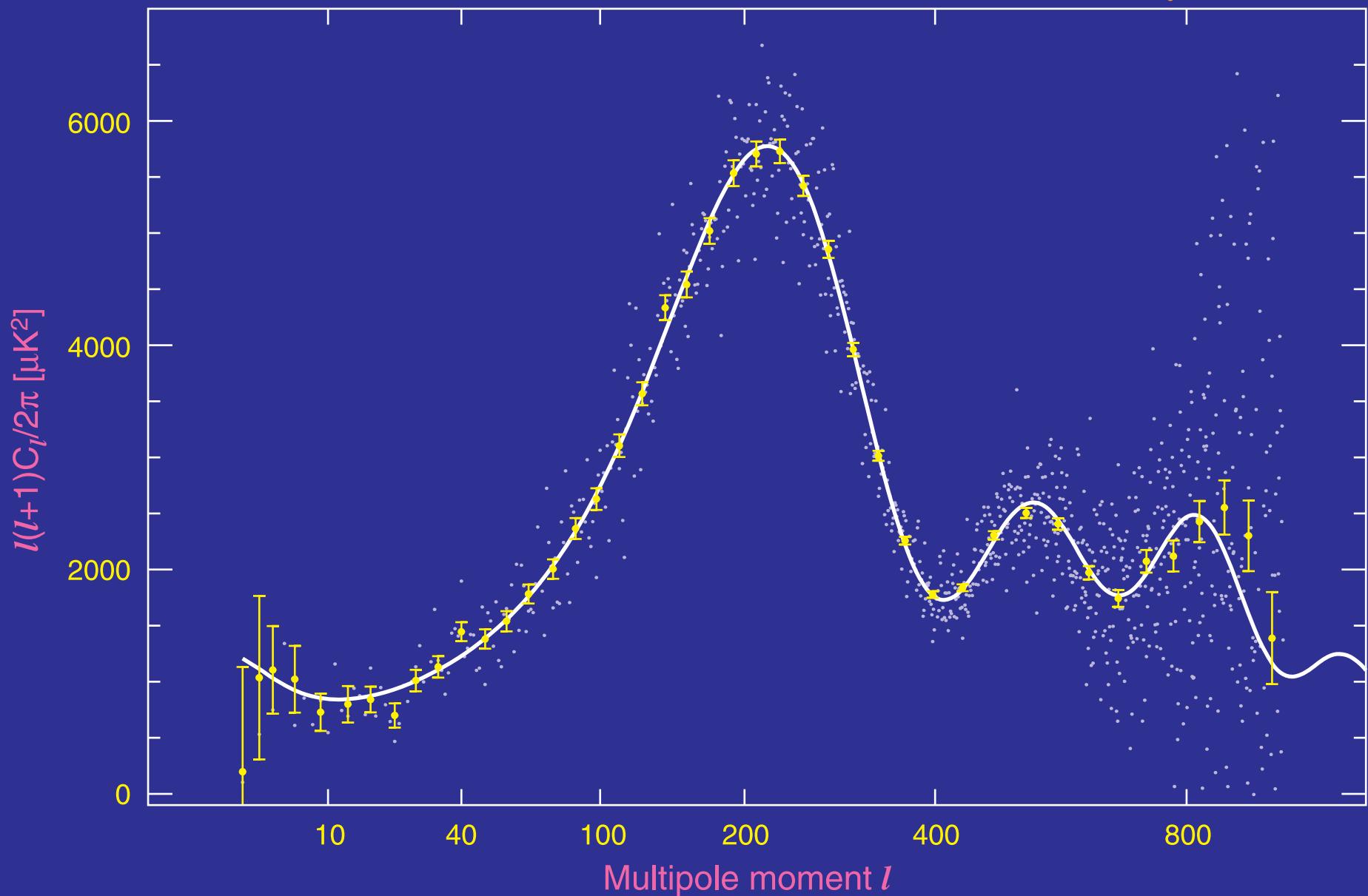
# Power Spectrum Past



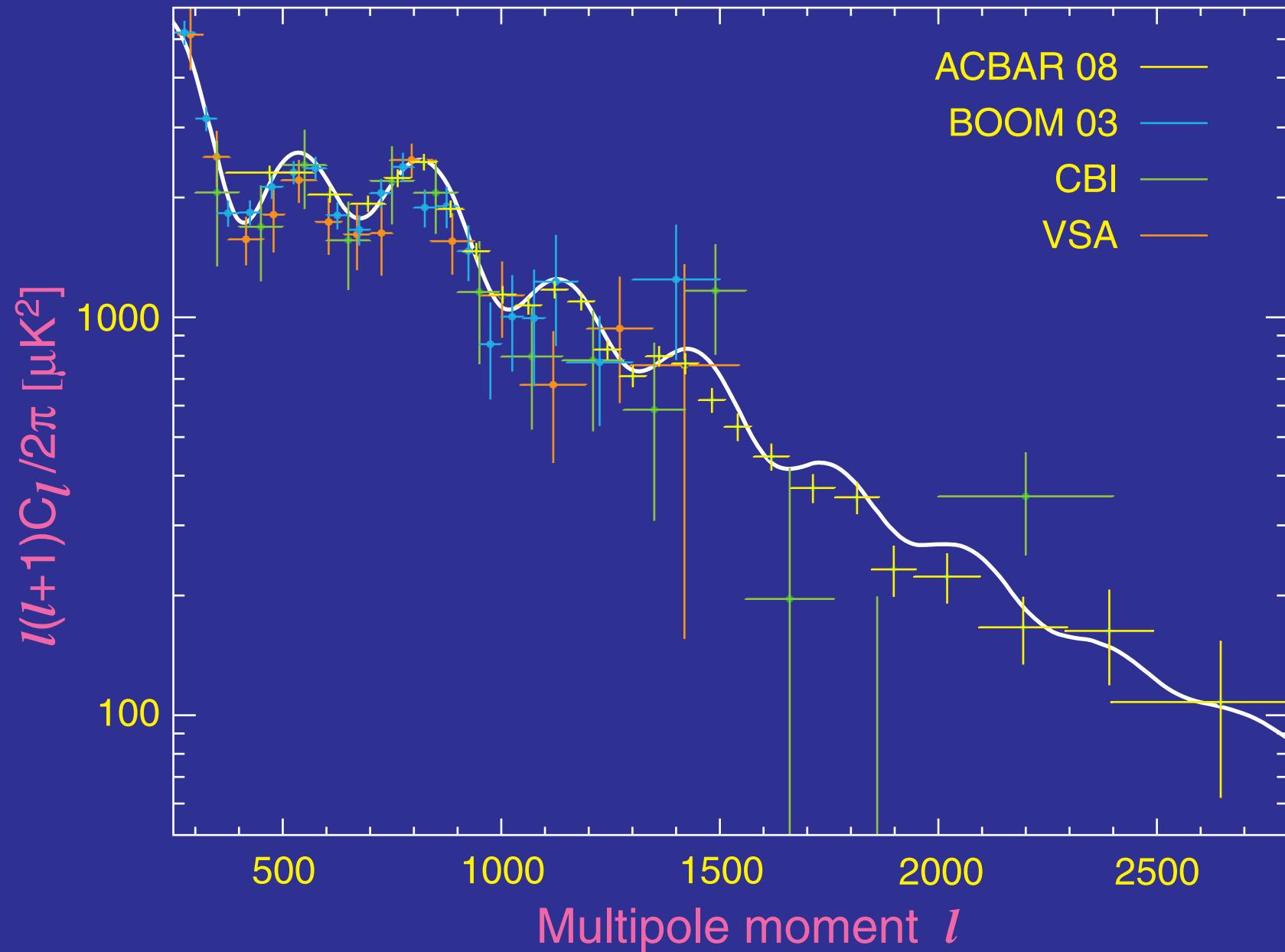
Present:  
Precision Tests of the Standard Model

# Power Spectrum Present

Dunkley et al (2008)



# Power Spectrum Present

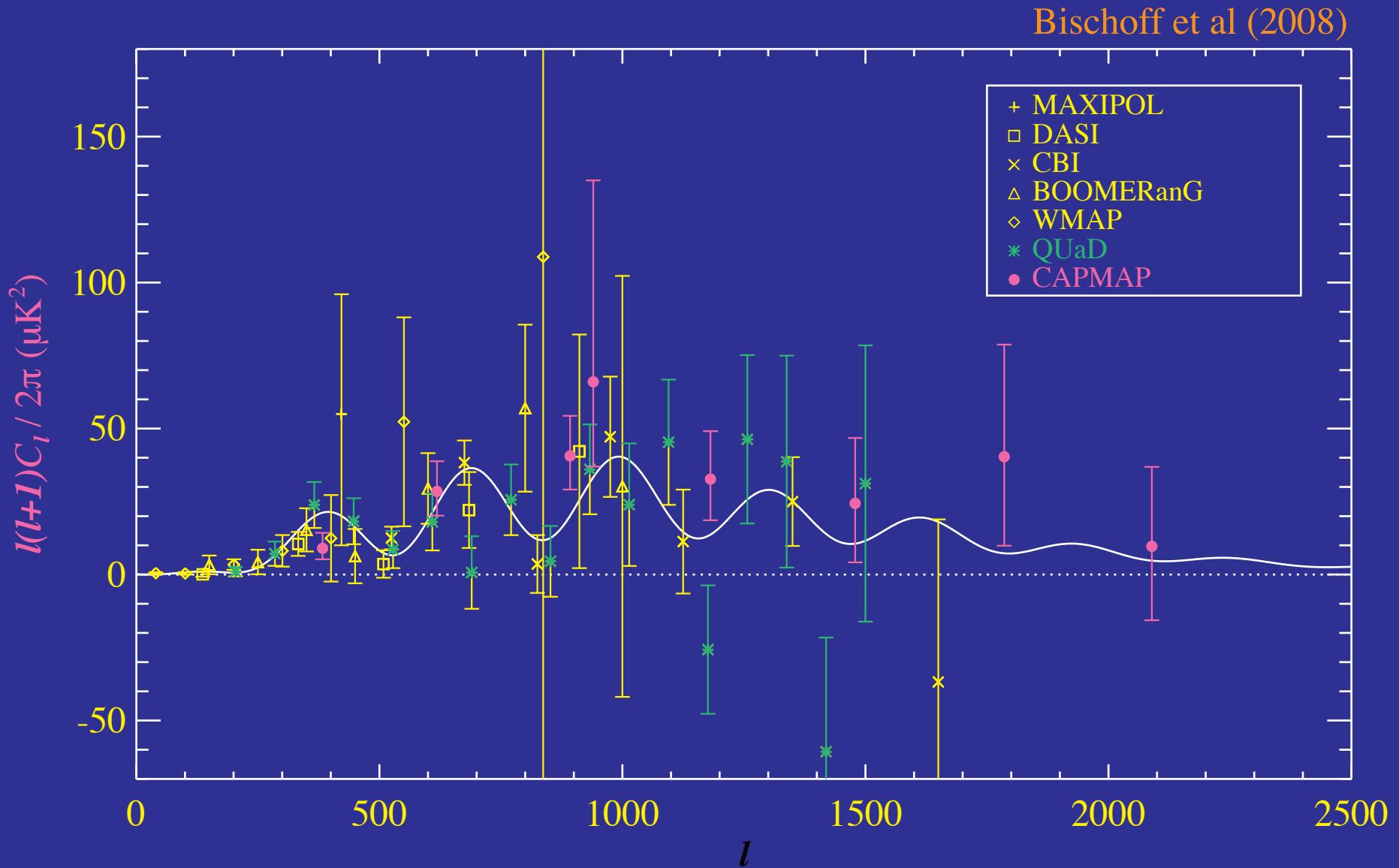


# Standard Model: Vanilla $\Lambda$ CDM

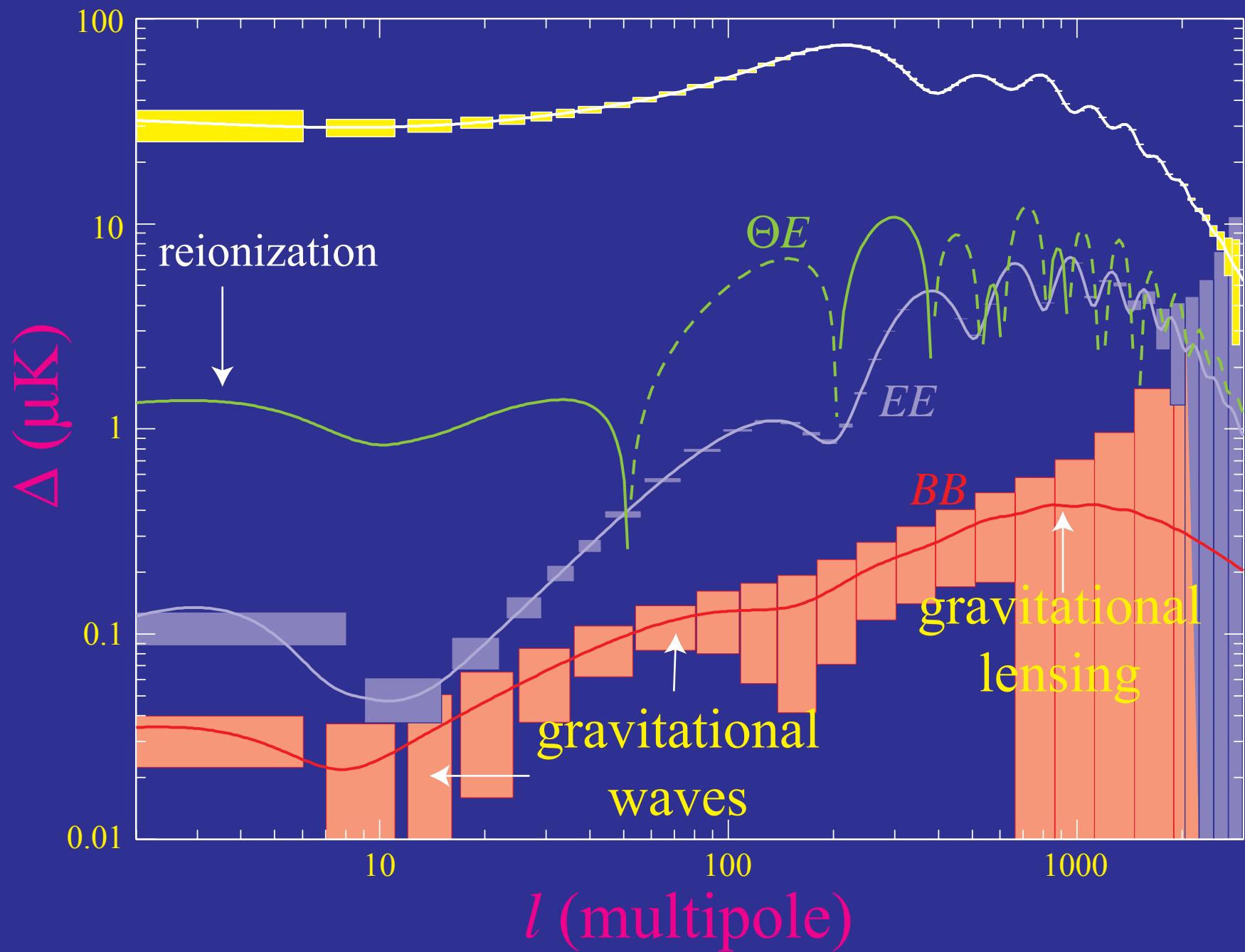
- 6 parameter  $\Lambda$ CDM model
- Fits WMAP and most other cosmological data

| Parameter                | 3 Year Mean                      | 5 Year Mean                      | 5 Year Max Like       |
|--------------------------|----------------------------------|----------------------------------|-----------------------|
| $100\Omega_b h^2$        | $2.229 \pm 0.073$                | $2.273 \pm 0.062$                | 2.27                  |
| $\Omega_c h^2$           | $0.1054 \pm 0.0078$              | $0.1099 \pm 0.0062$              | 0.108                 |
| $\Omega_\Lambda$         | $0.759 \pm 0.034$                | $0.742 \pm 0.030$                | 0.751                 |
| $n_s$                    | $0.958 \pm 0.016$                | $0.963^{+0.014}_{-0.015}$        | 0.961                 |
| $\tau$                   | $0.089 \pm 0.030$                | $0.087 \pm 0.017$                | 0.089                 |
| $\Delta_{\mathcal{R}}^2$ | $(2.35 \pm 0.13) \times 10^{-9}$ | $(2.41 \pm 0.11) \times 10^{-9}$ | $2.41 \times 10^{-9}$ |
| $\sigma_8$               | $0.761 \pm 0.049$                | $0.796 \pm 0.036$                | 0.787                 |
| $\Omega_m$               | $0.241 \pm 0.034$                | $0.258 \pm 0.030$                | 0.249                 |
| $\Omega_m h^2$           | $0.128 \pm 0.008$                | $0.1326 \pm 0.0063$              | 0.131                 |
| $H_0$                    | $73.2^{+3.1}_{-3.2}$             | $71.9^{+2.6}_{-2.7}$             | 72.4                  |
| $z_{\text{reion}}$       | $11.0 \pm 2.6$                   | $11.0 \pm 1.4$                   | 11.2                  |
| $t_0$                    | $13.73 \pm 0.16$                 | $13.69 \pm 0.13$                 | 13.7                  |

# Power Spectrum Present



# Power Spectrum Future



# Inflation & Early Universe

# Inflation Past

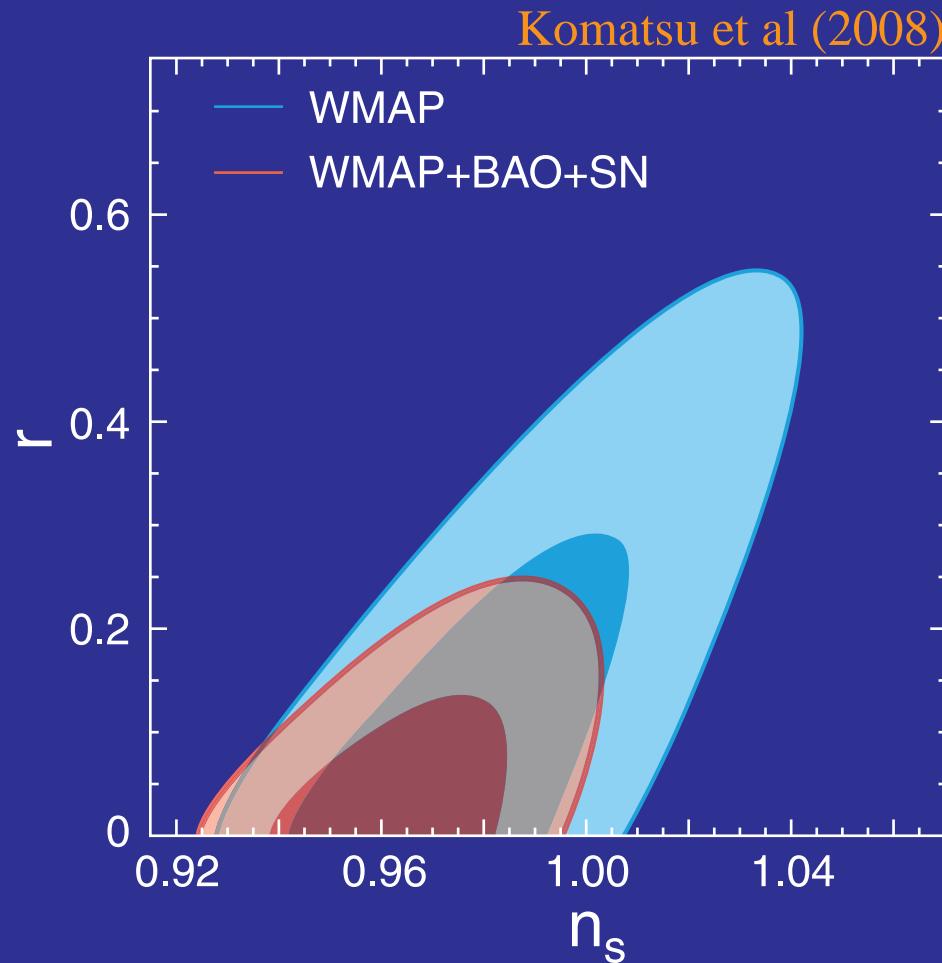
- Superhorizon correlations  
(acoustic coherence, polarization corr.)
- Spatially flat geometry  
(angular peak scale)
- Adiabatic fluctuations  
(peak morphology)
- Nearly scale invariant fluctuations  
(broadband power, small red tilt favored)
- Gaussian fluctuations  
(but  $f_{\text{nl}} > \text{few}$  would rule out single field slow roll)

# Inflation Present

- Tilt (or gravitational waves) indicates that one of the slow roll parameters finite (ignoring exotic high-z reionization)
- Constraints in the  $r-n_s$  plane test classes of models
- Upper limit on gravity waves put an upper limit on  $V'/V$  and hence an upper limit on how far the inflaton rolls
- Given functional form of  $V$ , constraints on the flatness of potential when the horizon left the horizon predict too many (or few) efolds of further inflation
- Non-Gaussian fluctuations at  $fnl \sim 50-100$ ?

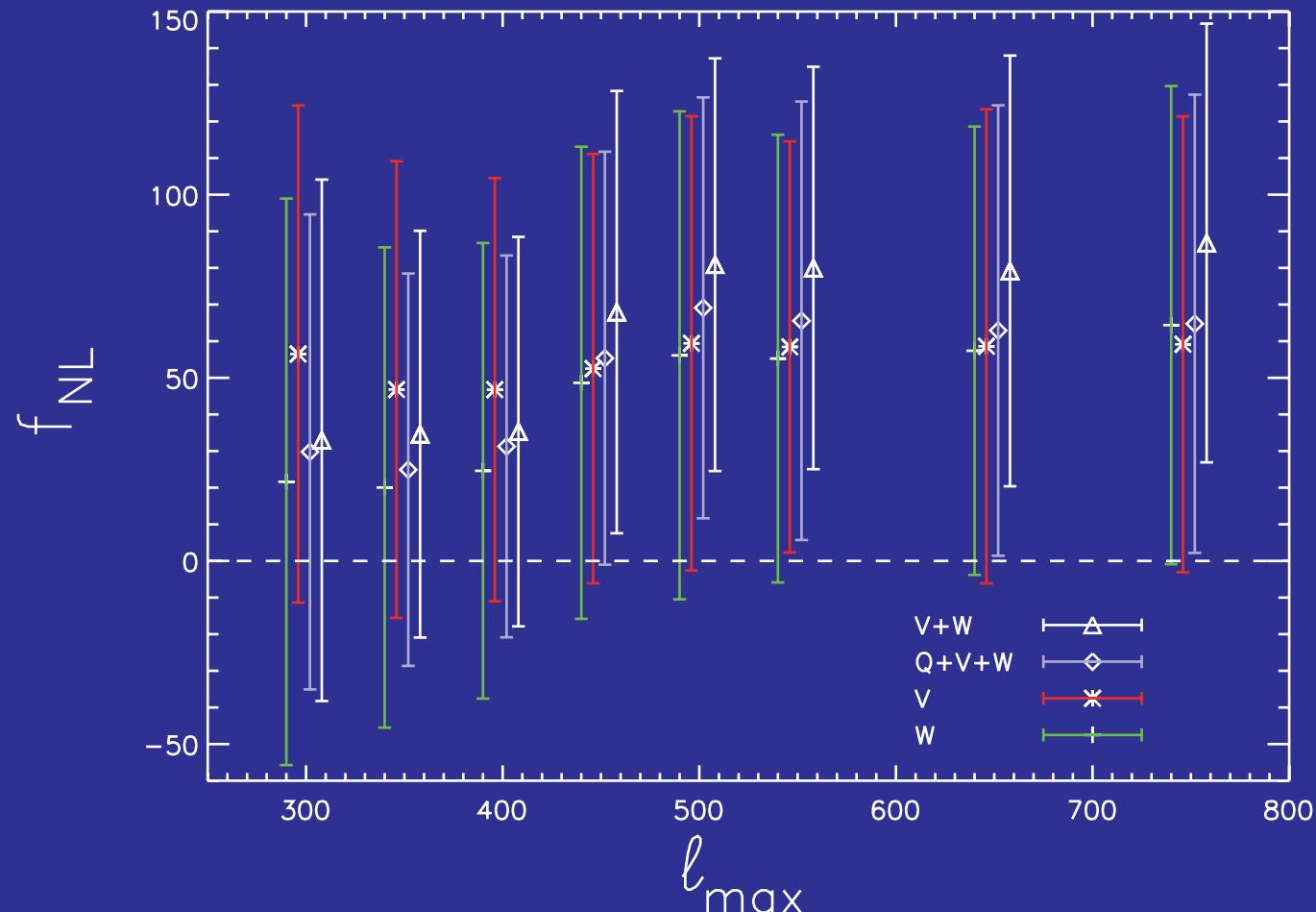
# Inflationary Constraints

- Tilt mildly favored over tensors as explaining small scale suppression
- Specific models of inflation relate  $r$ - $n_s$  through  $V'$ ,  $V''$
- Small tensors and  $n_s \sim 1$  may make inflation continue for too many efolds



# Primordial Non-Gaussianity $f_{\text{nl}}$

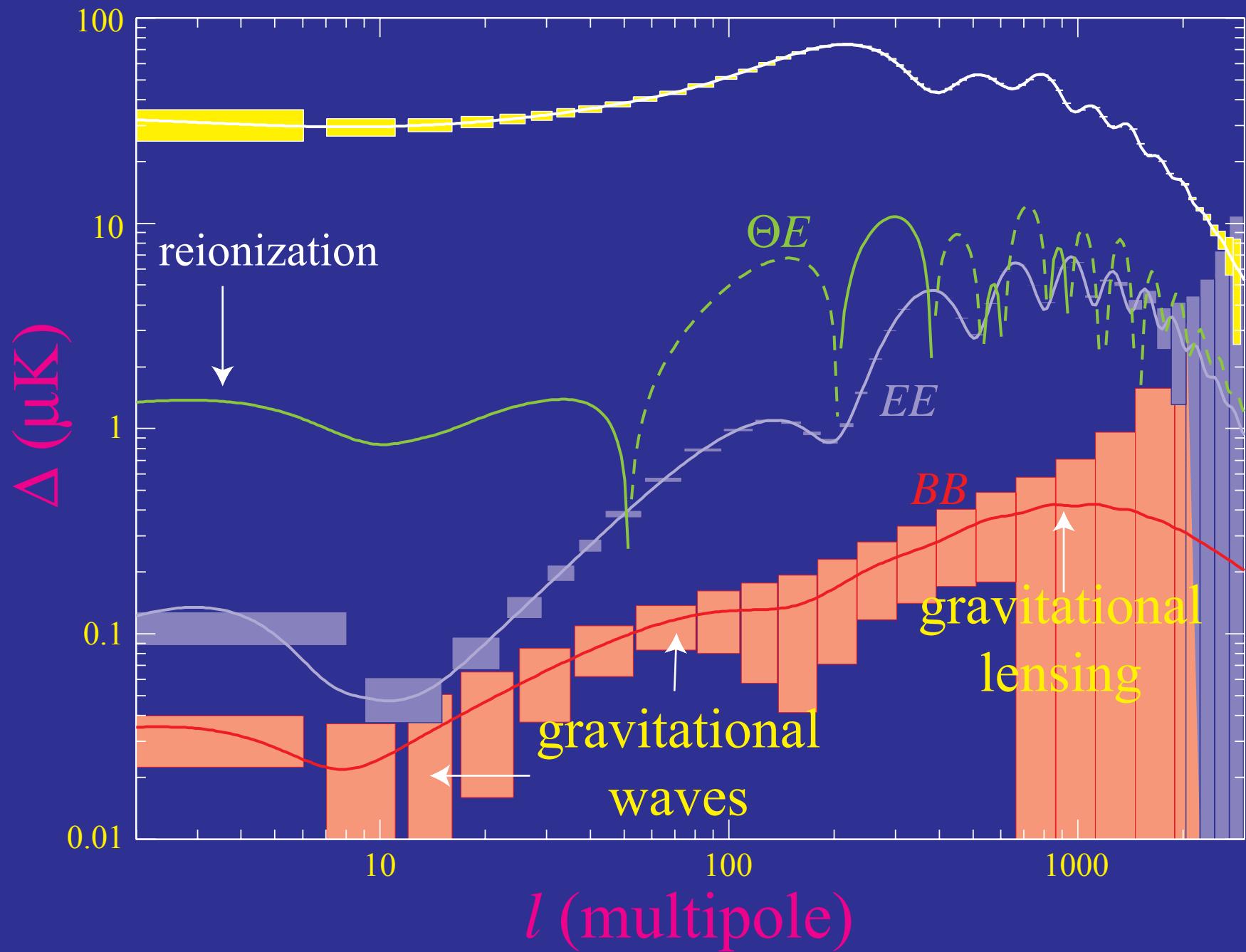
- Local second order non-Gaussianity:  $\Phi_{\text{nl}} = \Phi + f_{\text{nl}}(\Phi^2 - \langle \Phi^2 \rangle)$
- WMAP3 Kp0+:  $27 < f_{\text{nl}} < 147$  (95% CL) (Yadav & Wandelt 2007)
- WMAP5 KQ75:  $-5 < f_{\text{nl}} < 111$  (95% CL) (Komatsu et al 2008)



# Inflation Future

- Planck can test Gaussianity down to  $f_{nl} \sim$  few
- Gravitational wave power proportional to energy scale to 4th power
- B-modes potentially observable for  $V^{1/4} > 3 \times 10^{15}$  GeV with removal of lensing B-modes and foregrounds
- Measuring both the reionization bump and recombination peak tests slow roll consistency relation by constraining tensor tilt
- Requires measurement and model-independent interpretation of reionization E-modes

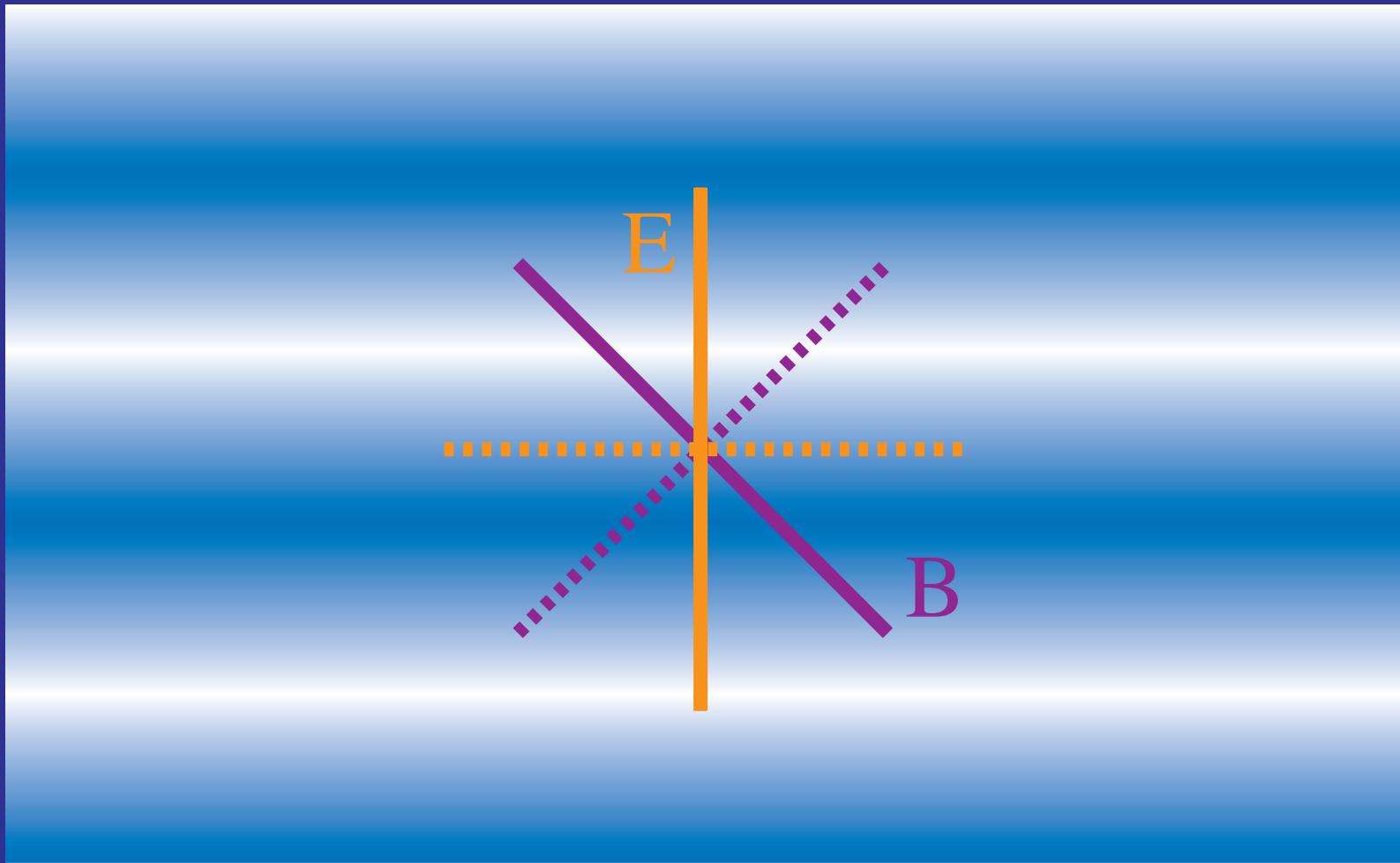
# Power Spectrum Future



# Electric & Magnetic Polarization

(a.k.a. gradient & curl)

- Alignment of principal vs polarization axes  
(curvature matrix vs polarization direction)

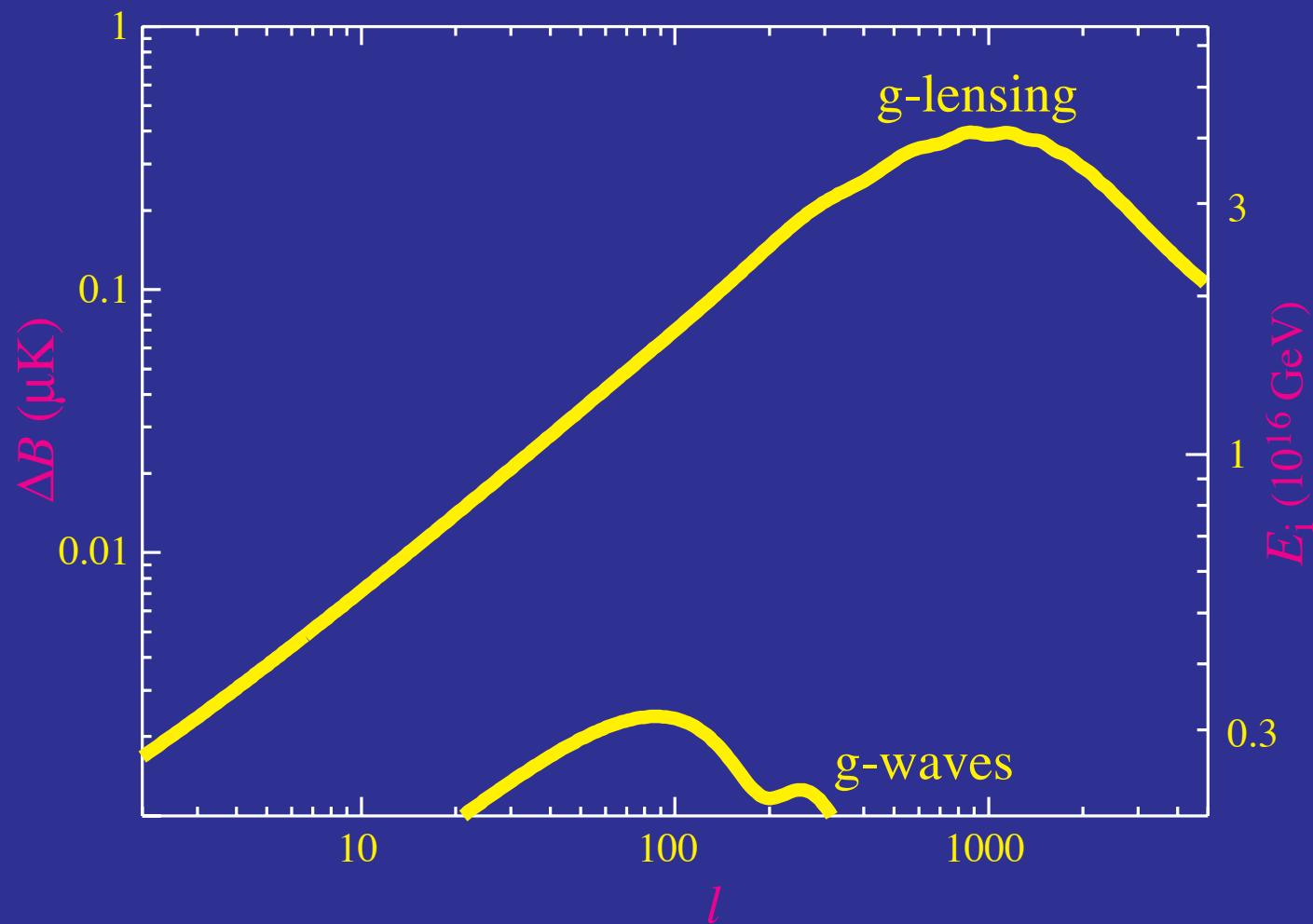


Kamionkowski, Kosowsky, Stebbins (1997)

Zaldarriaga & Seljak (1997)

# De-Lensing the Polarization

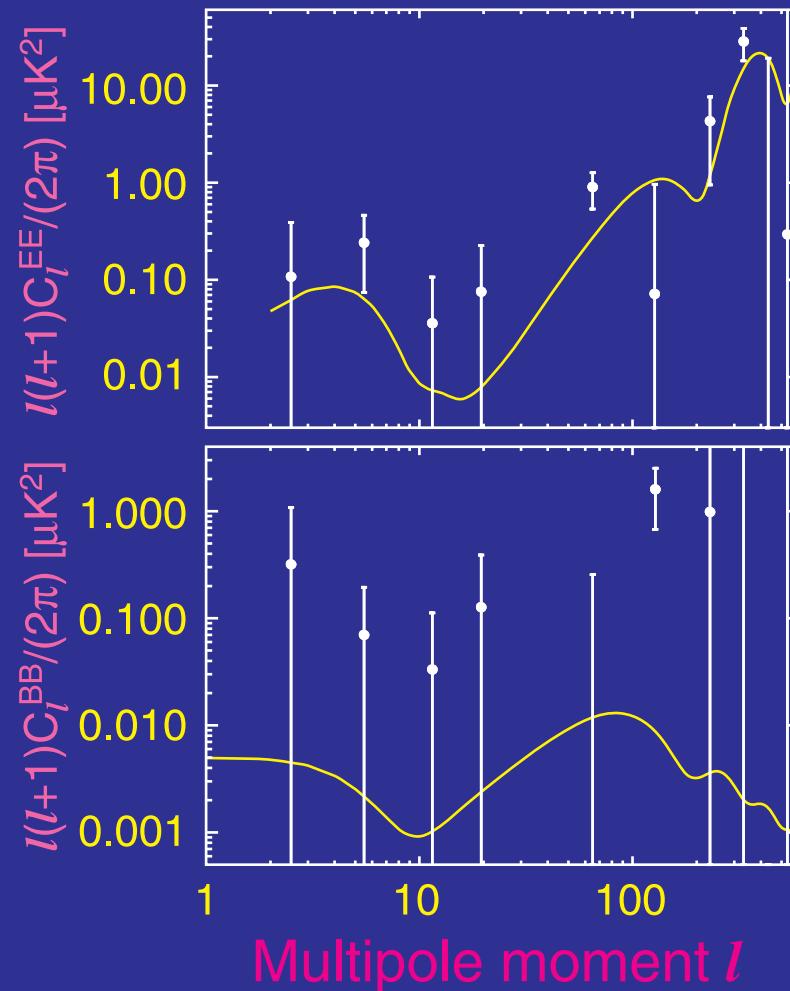
- Gravitational lensing contamination of B-modes from gravitational waves cleaned to  $E_l \sim 0.3 \times 10^{16} \text{ GeV}$   
Hu & Okamoto (2002); Knox & Song (2002); Cooray, Kedsen, Kamionkowski (2002)
- Potentially further with maximum likelihood Hirata & Seljak (2004)



# Reionization

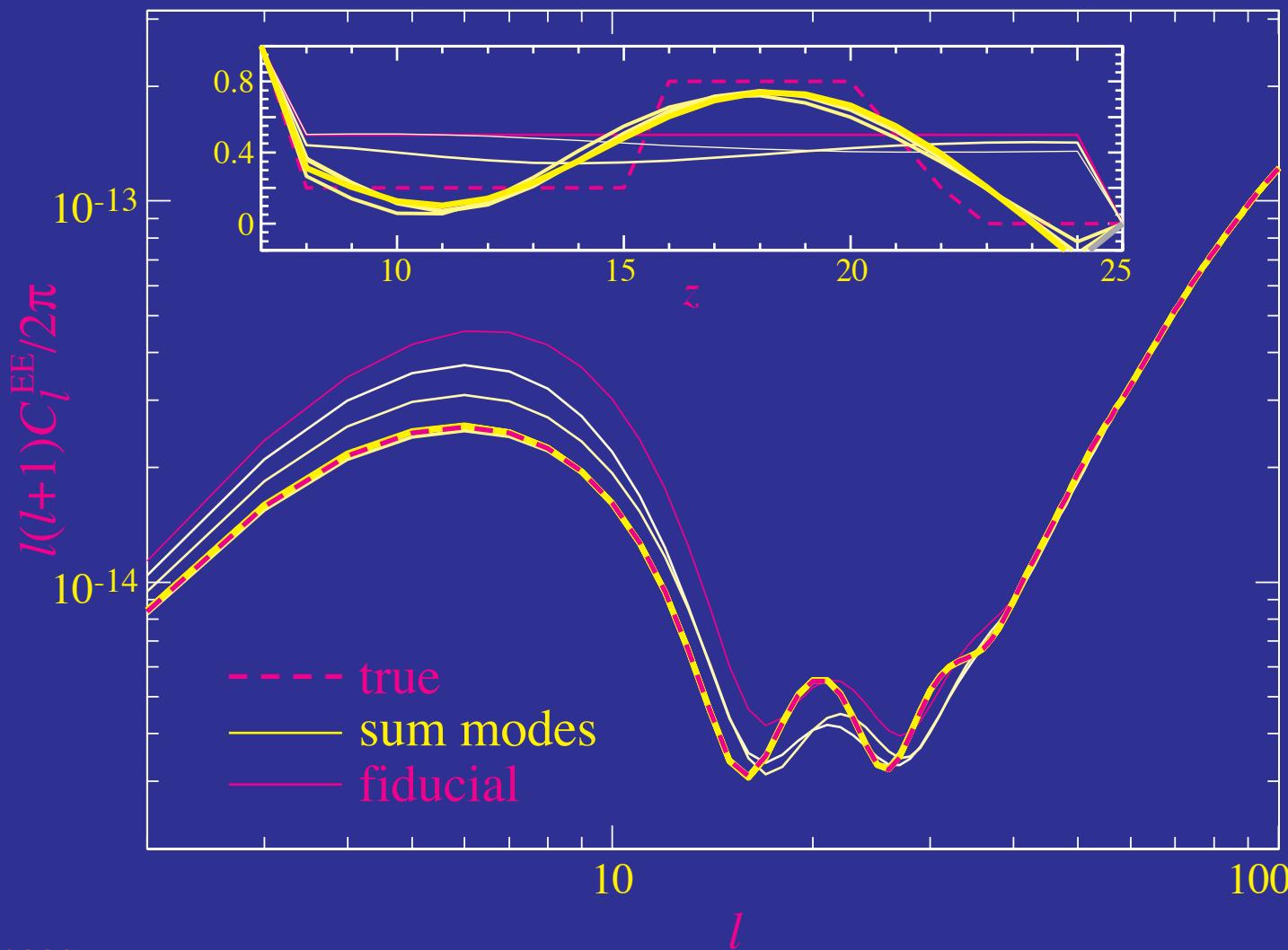
# Instantaneous Reionization

- WMAP data constrains optical depth for instantaneous models of  $\tau=0.087\pm0.017$
- Upper limit on gravitational waves weaker than from temperature



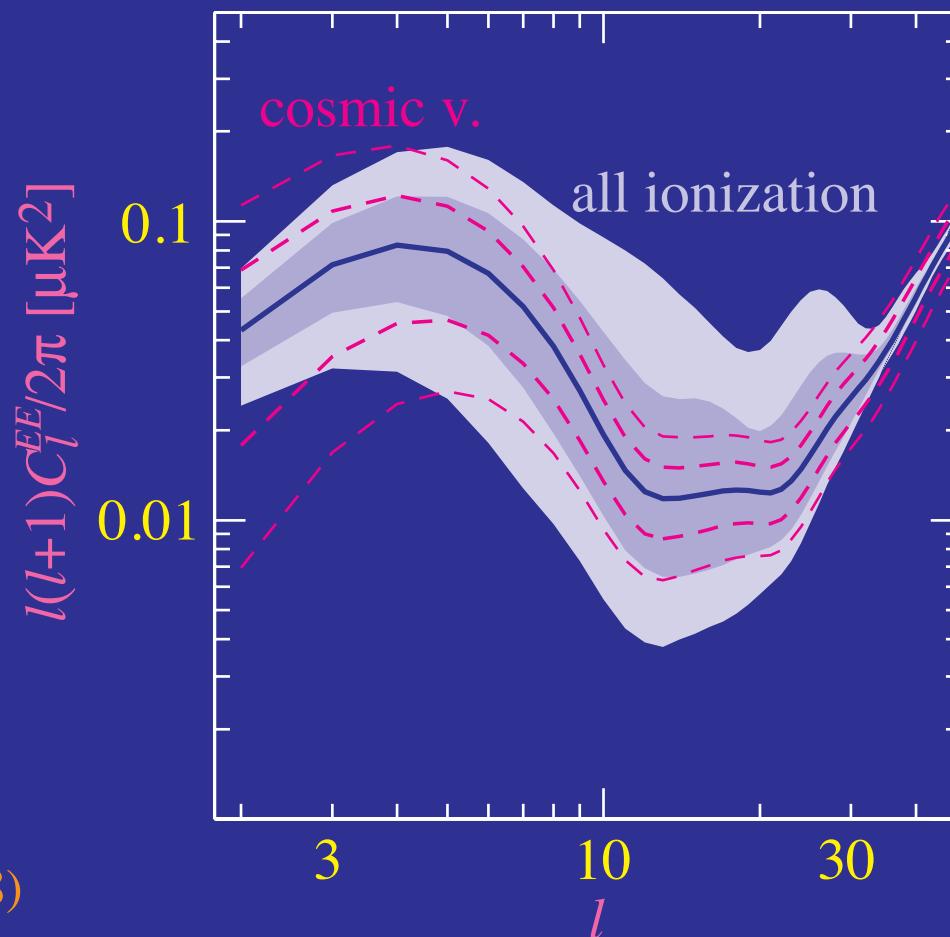
# Representation in Modes

- Reproduces the power spectrum and net optical depth (actual  $\tau=0.1375$  vs 0.1377); indicates whether multiple physical mechanisms suggested



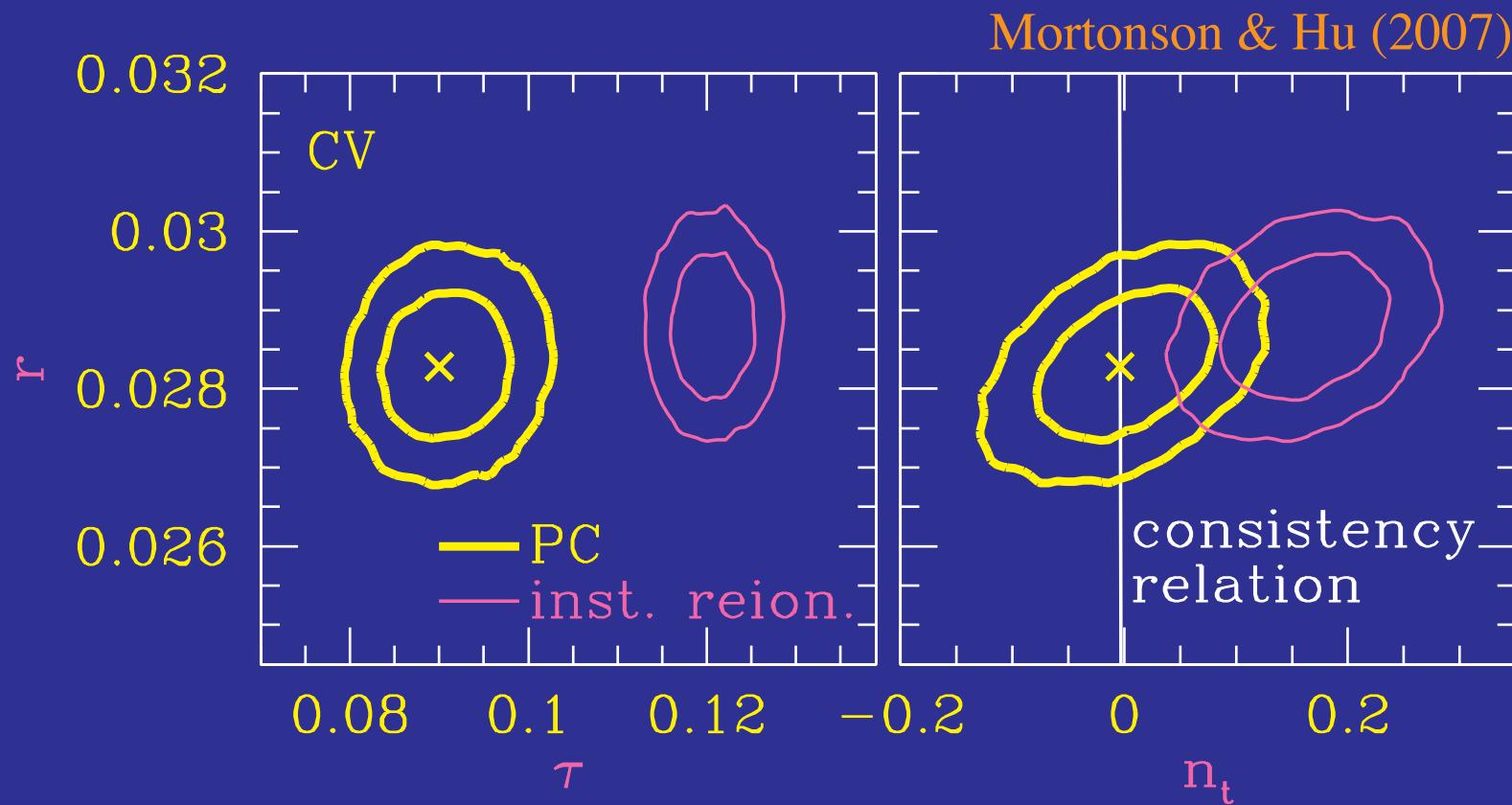
# Model-Independent Reionization

- All possible ionization histories at  $z < 30$
- Detections at  $20 < l < 30$  required to further constrain general ionization which widens the  $\tau$ - $n_s$  degeneracy allowing  $n_s = 1$
- Quadrupole & octopole predicted to better than cosmic variance test  $\Lambda$ CDM for anomalies



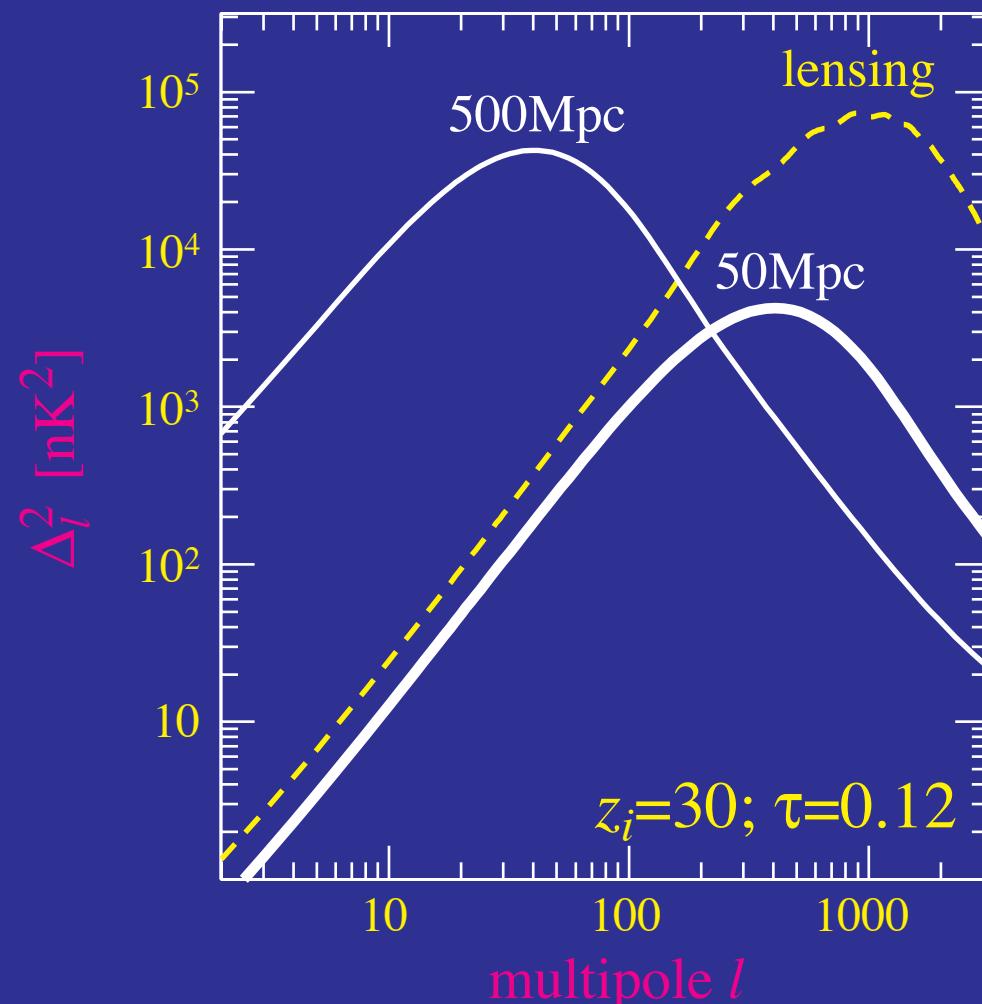
# Consistency Relation & Reionization

- By assuming the wrong ionization history can falsely rule out consistency relation
- Principal components eliminate possible biases



# B-mode Contamination from Reionization

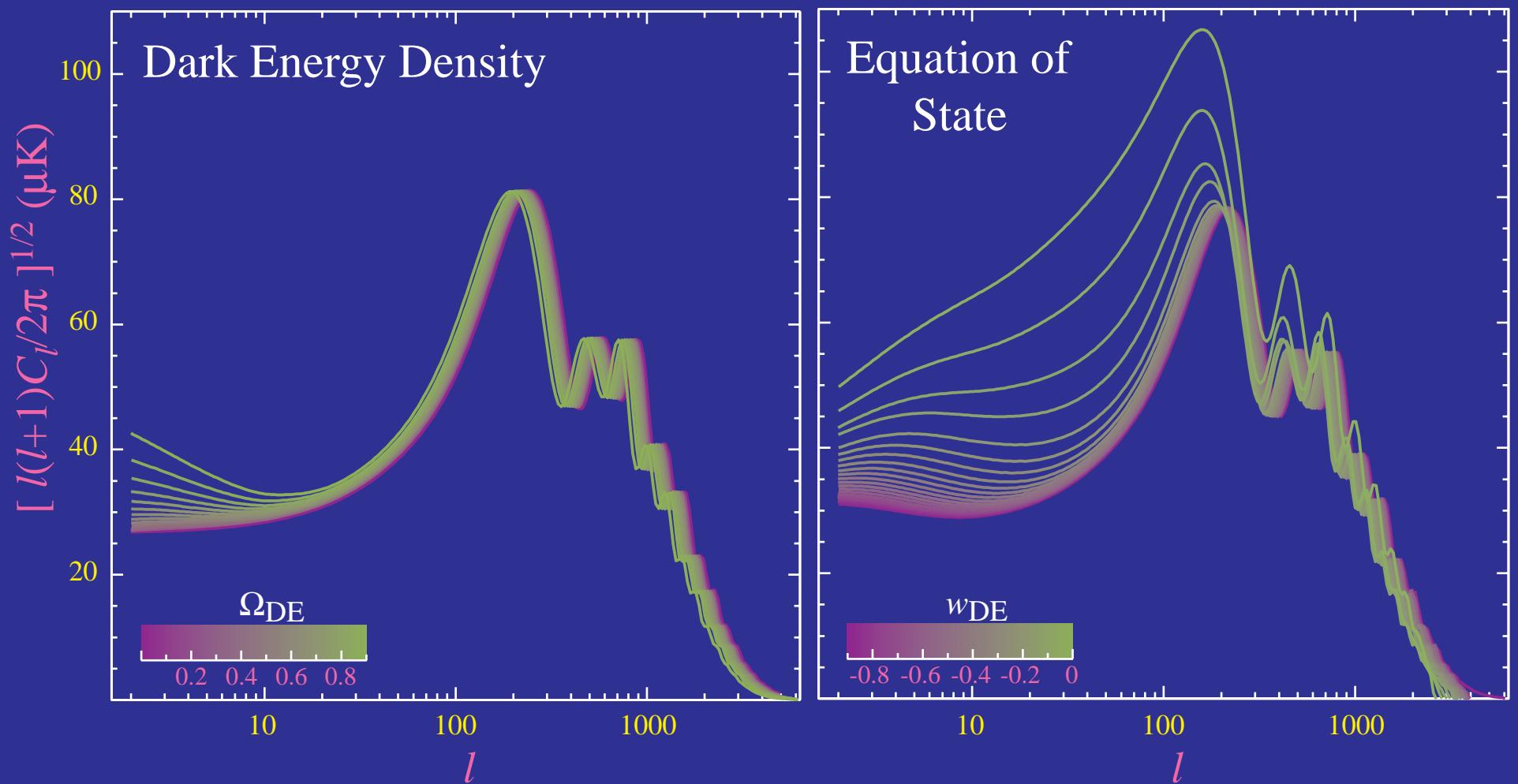
- Inhomogeneous reionization modulates polarization into B-modes  
(Hu 2000)
- Large signals if ionization bubbles >100Mpc at  $z \sim 20-30$



# Cosmic Acceleration

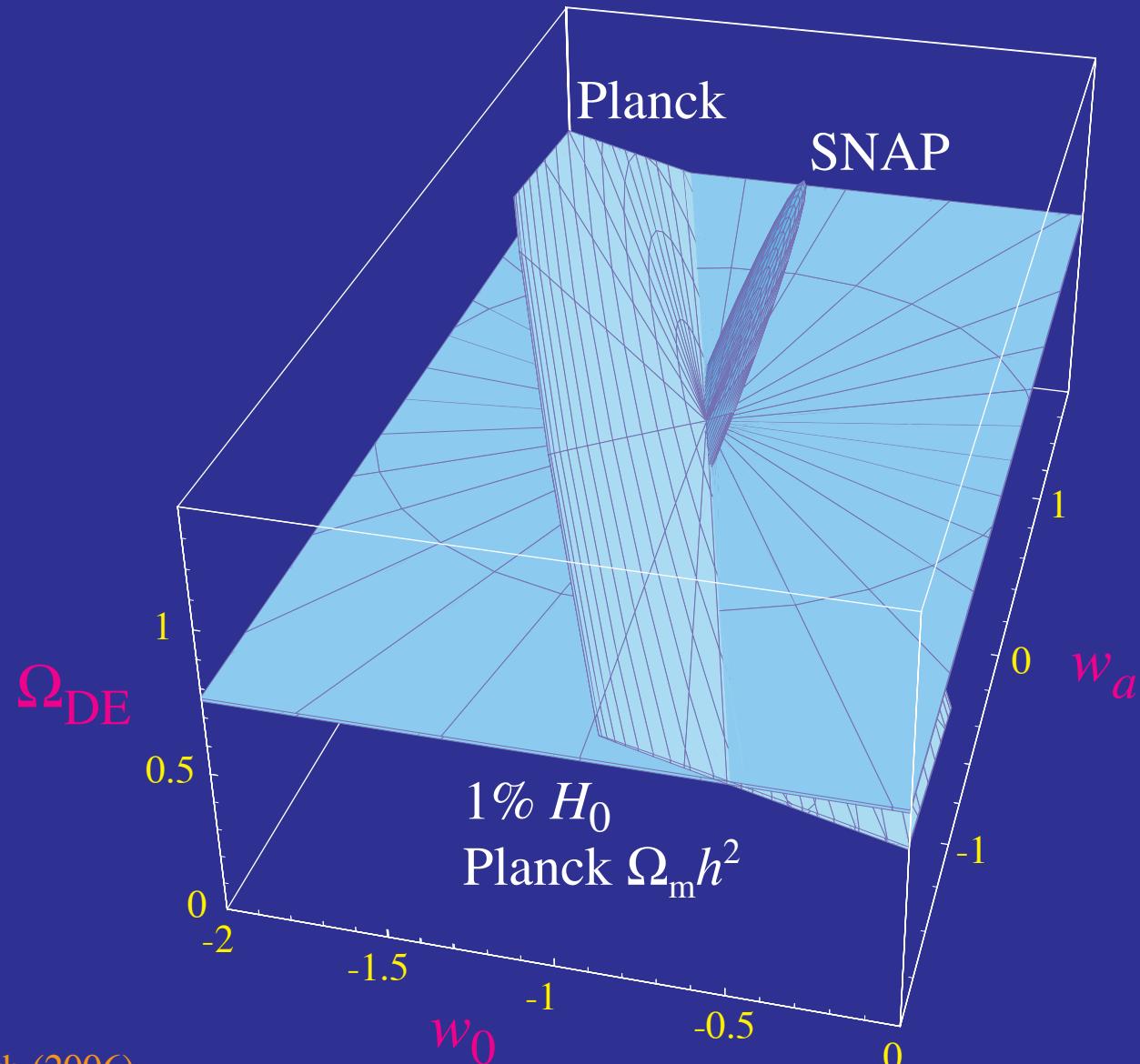
# Dark Energy

- Peaks measure distance to recombination
- ISW effect constrains dynamics of acceleration



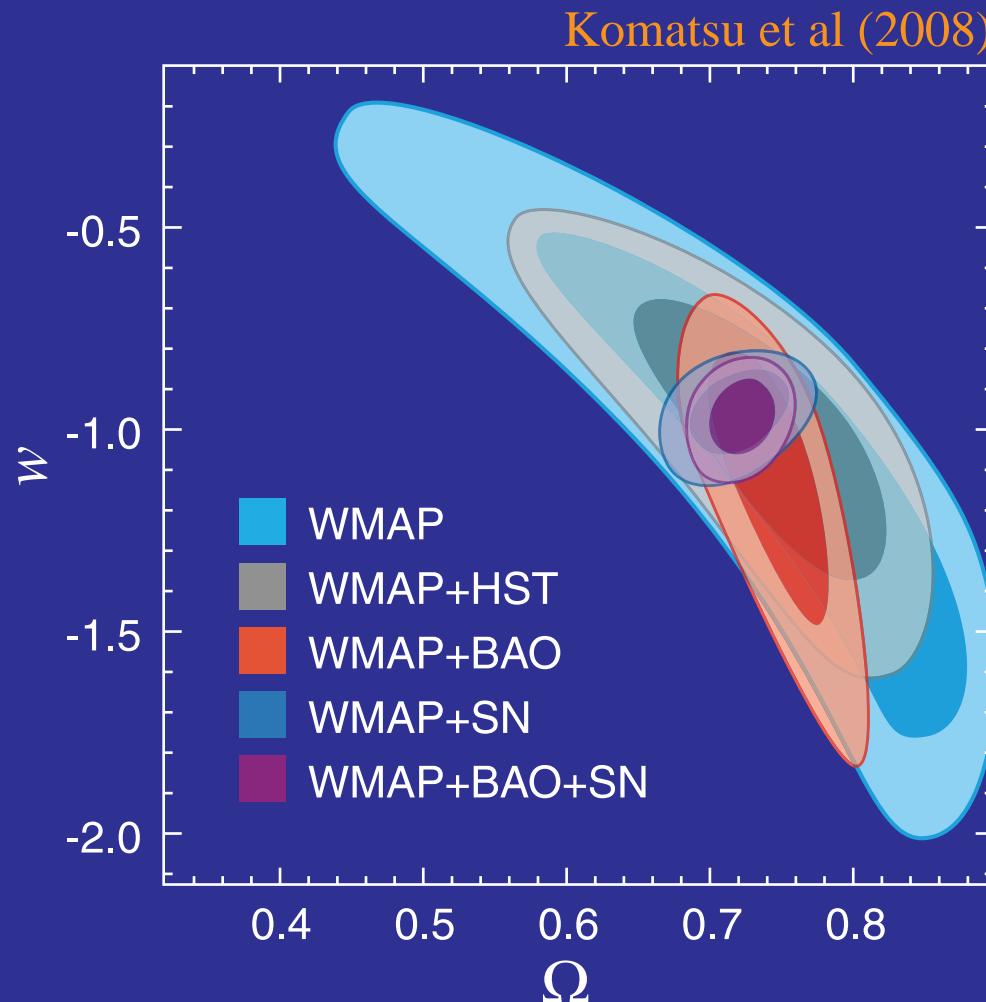
# Flat Universe Precision

- Planck acoustic peaks, 1%  $H_0$ , SNAP SNe to  $z=1.7$  in a flat universe



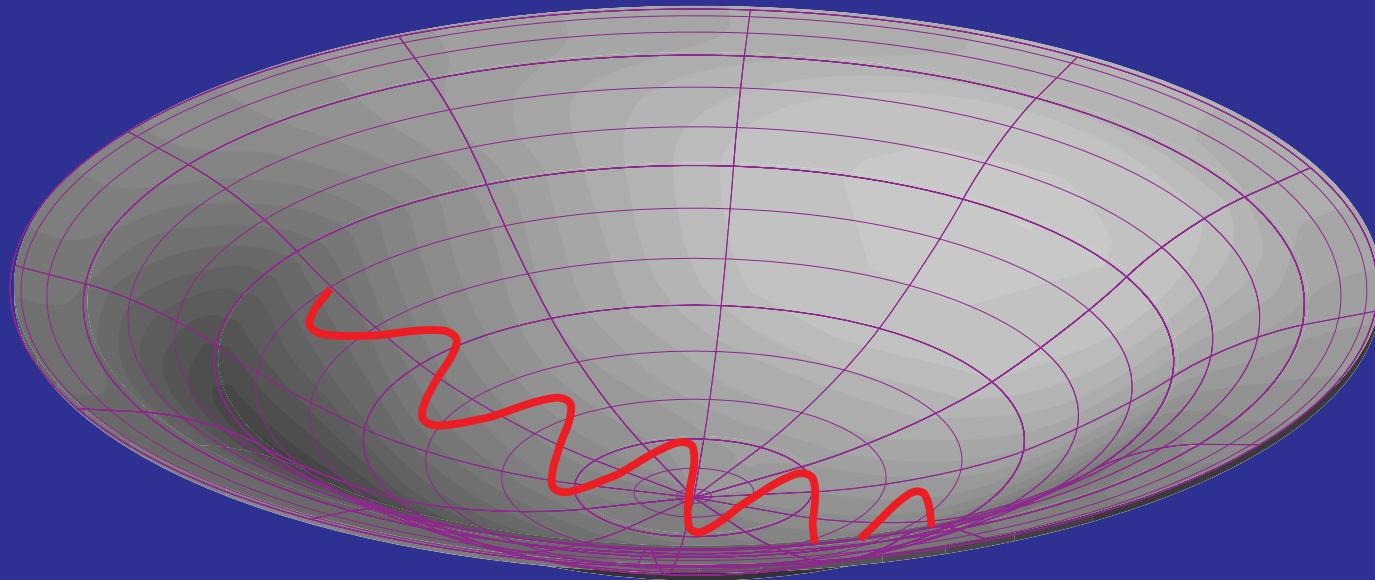
# Dark Energy

- Flat  $\Lambda$ CDM fully consistent with CMB and other distance measures
- Constant  $w=p/\rho$  constrained as  $-0.097 < 1+w < 0.142$  (95% CL)



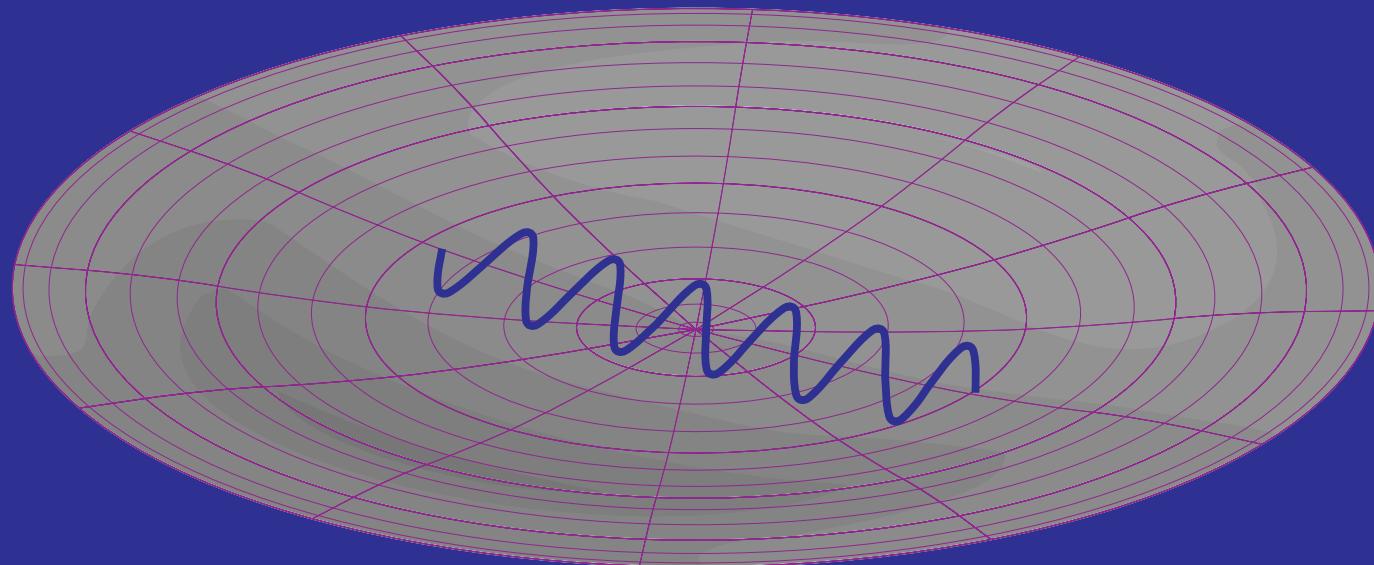
# ISW Effect

- Gravitational blueshift on infall does not cancel redshift on climbing out
- Contraction of spatial metric doubles the effect:  $\Delta T/T = 2\Delta\Phi$
- Effect from potential hills and wells cancel on small scales



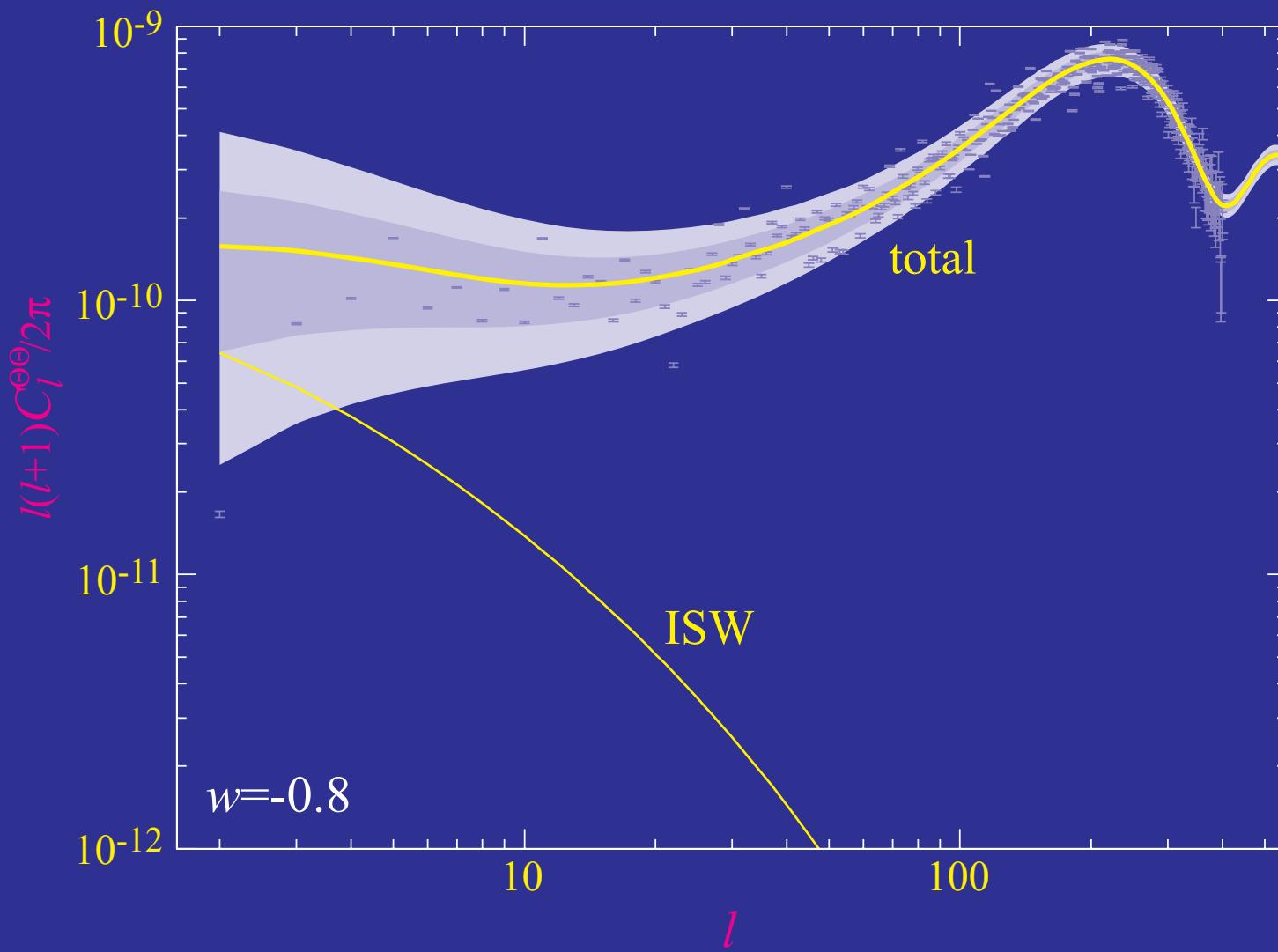
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# ISW Effect

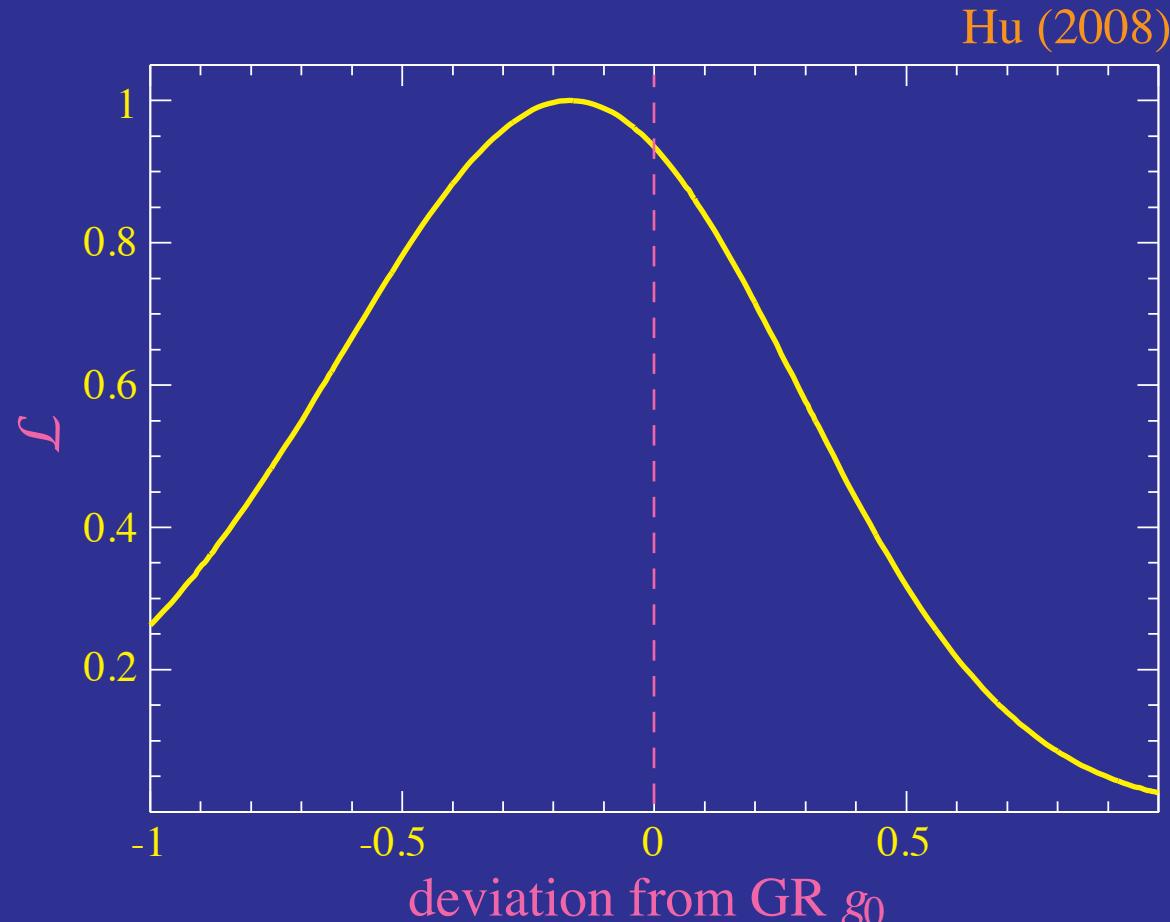
- ISW effect hidden in the temperature power spectrum by primary anisotropy and cosmic variance



[plot: Hu & Scranton (2004)]

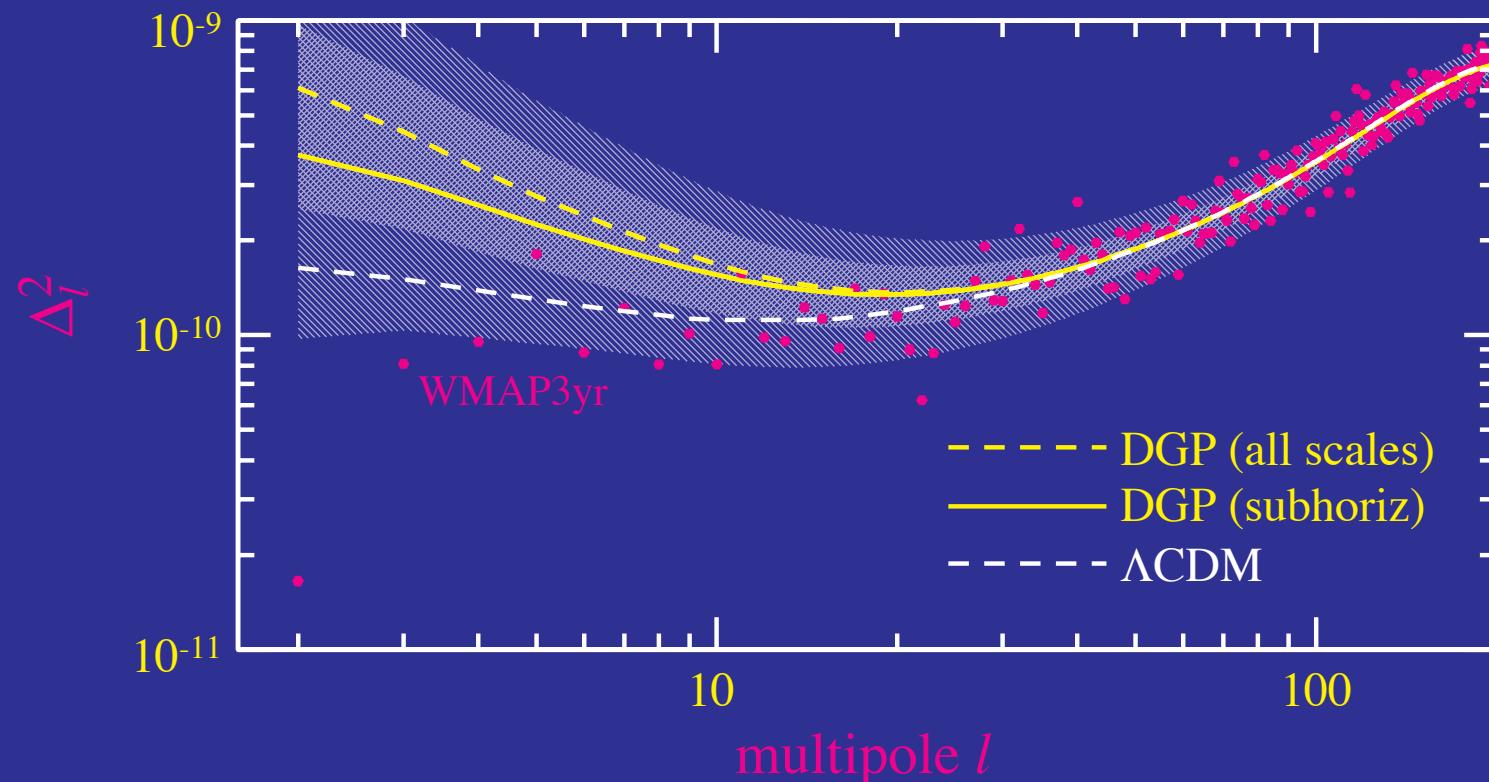
# Parameterized Post-Friedmann

- Parameterizing the degrees of freedom associated with metric modification of gravity that explain cosmic acceleration
- Simple models that add in only one extra scale to explain acceleration tend to predict substantial changes near horizon and hence ISW



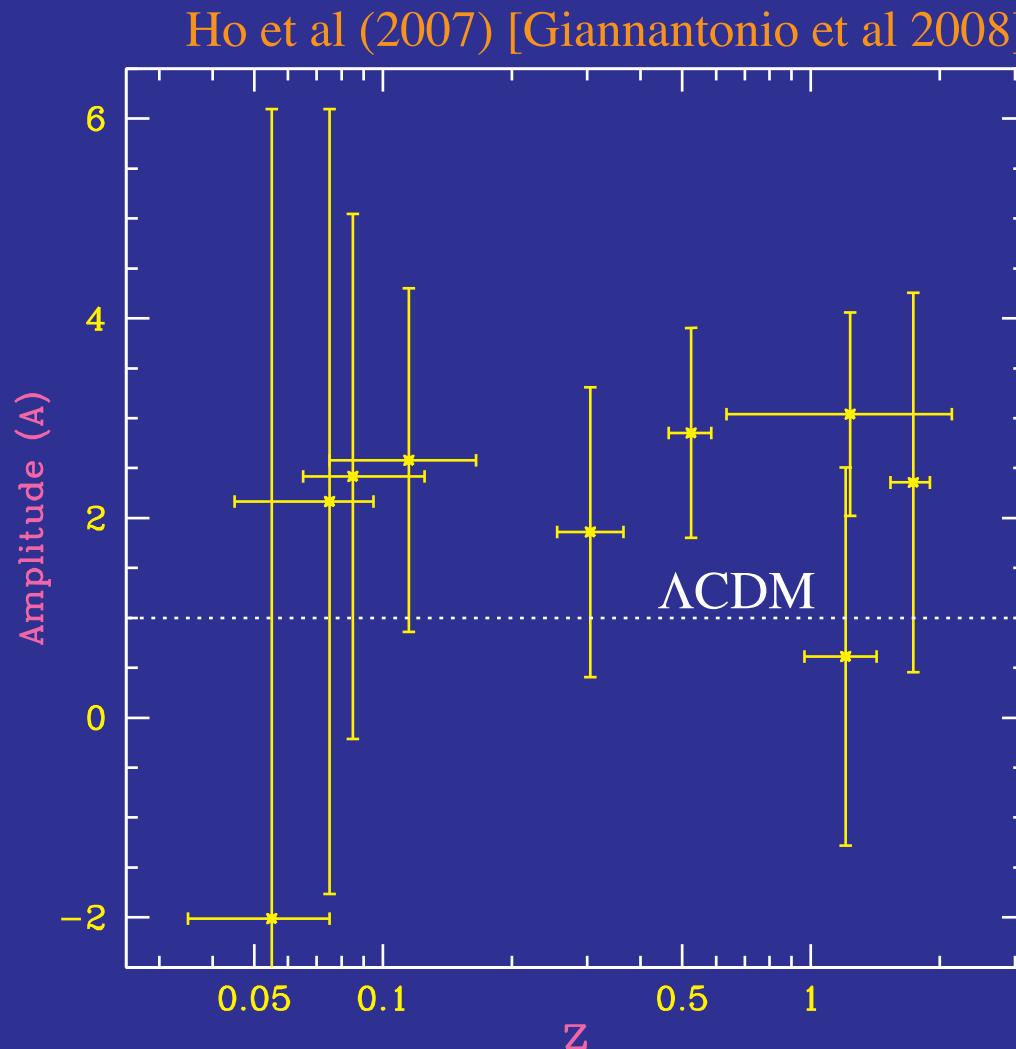
# DGP Example

- Difference in expansion history gives excess decay of grav. potential on **subhorizon scales** (Lue, Scoccimarro, Starkmann 2004; Koyama & Maartins 2005)
- Self-consistent iterative solution of **master equation** dynamics in the bulk enhances decay further on **horizon scales** and beyond



# ISW-Galaxy Correlation

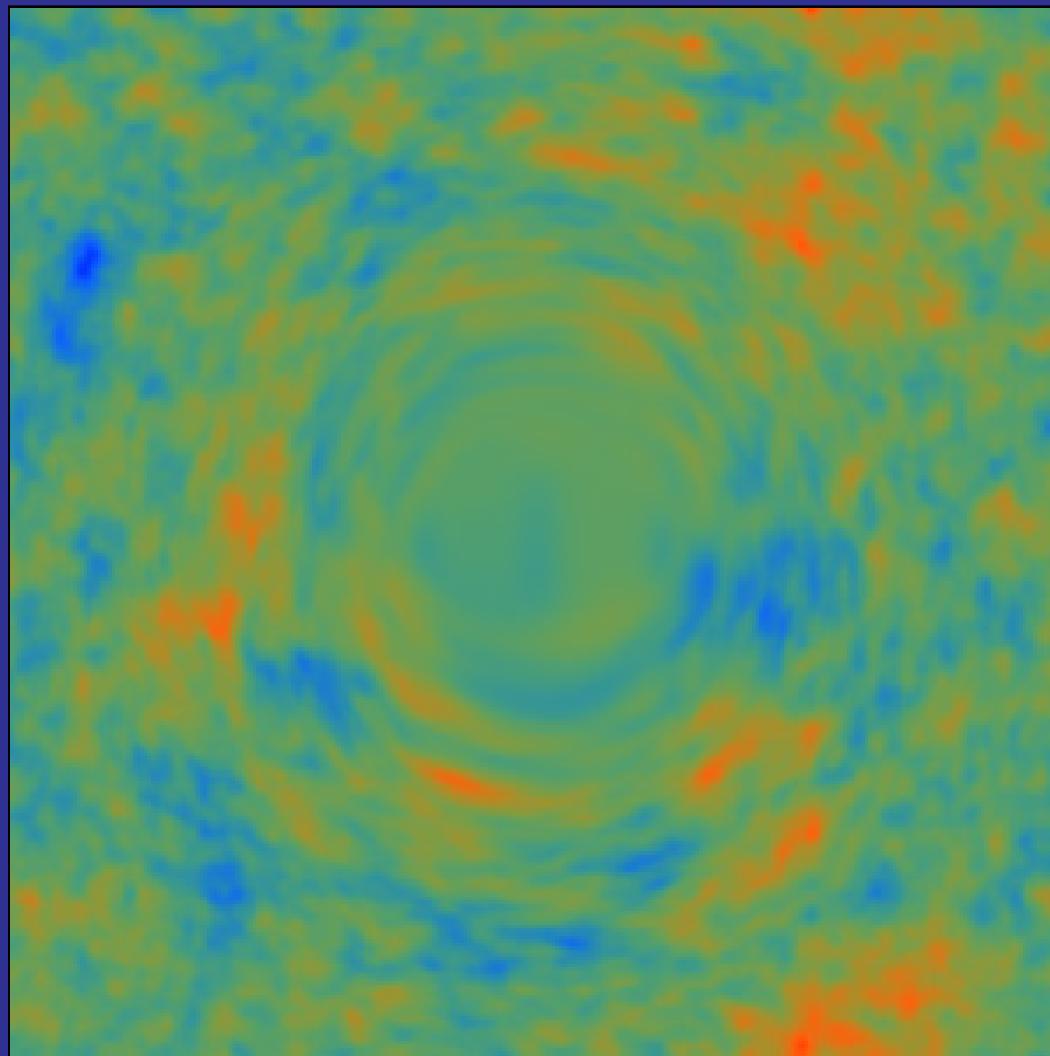
- $\sim 4\sigma$  joint detection of ISW correlation with large scale structure (galaxies)
- $\sim 2\sigma$  high compared with  $\Lambda$ CDM



# Gravitational Lensing

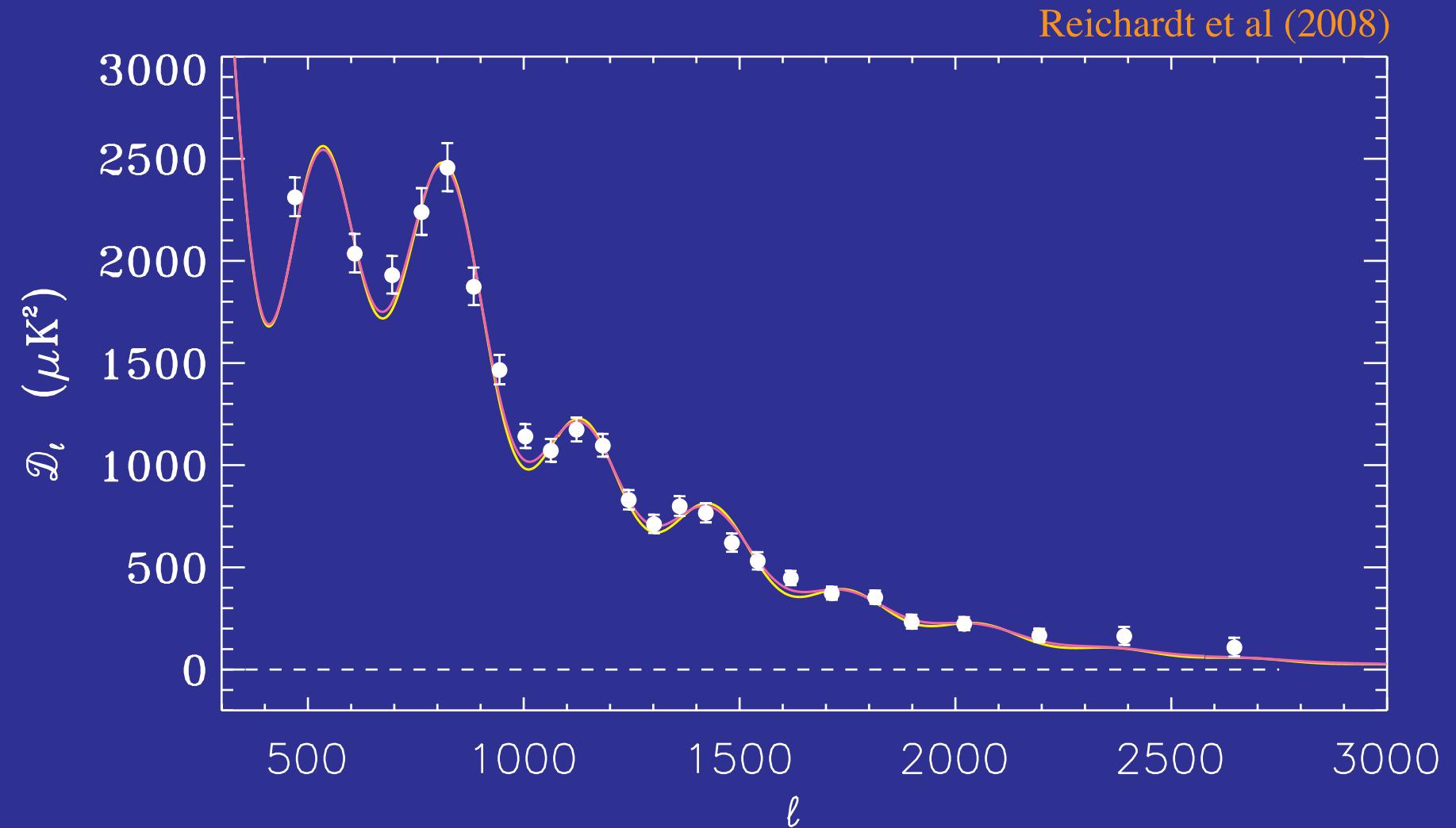
# Example of Weak Lensing

- Toy example of lensing of the CMB primary anisotropies
- Shearing of the image



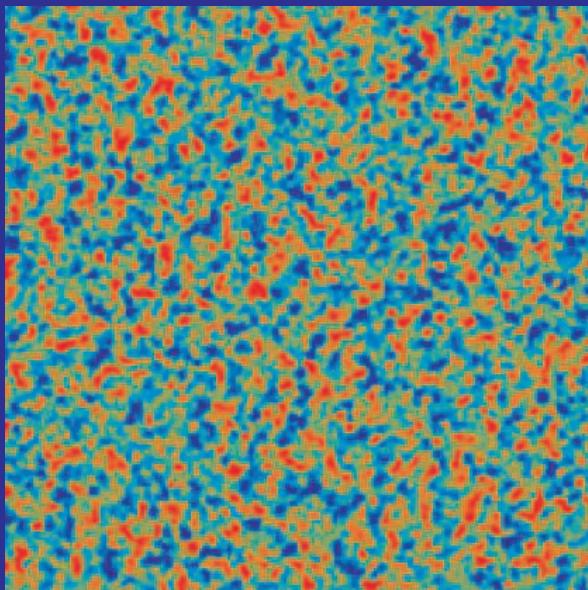
# Lensing Smoothing

- Lensing smooths acoustic peaks and is favored by ACBAR data ( $\sim 3\sigma$ )

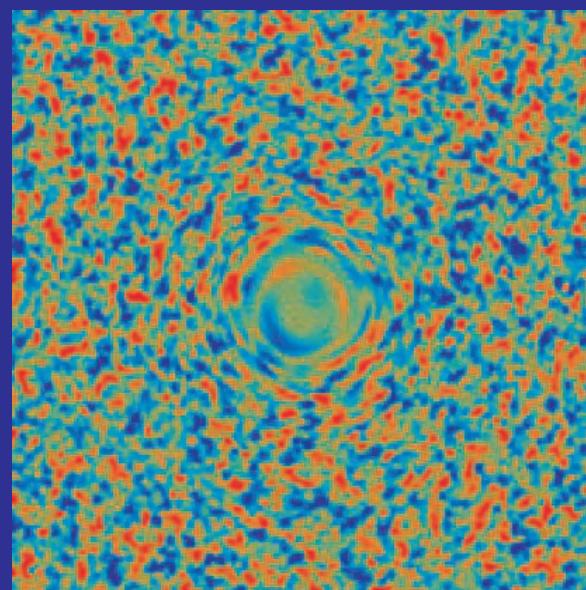


# Polarization Lensing

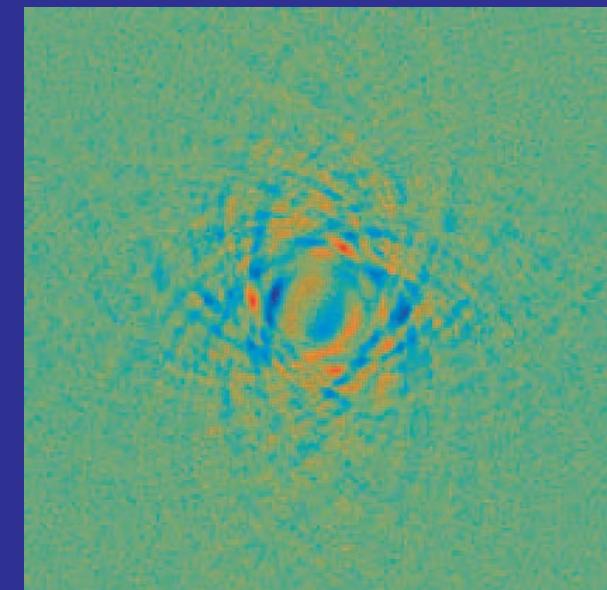
- Since  $E$  and  $B$  denote the relationship between the polarization amplitude and direction, warping due to lensing creates  $B$ -modes



Original

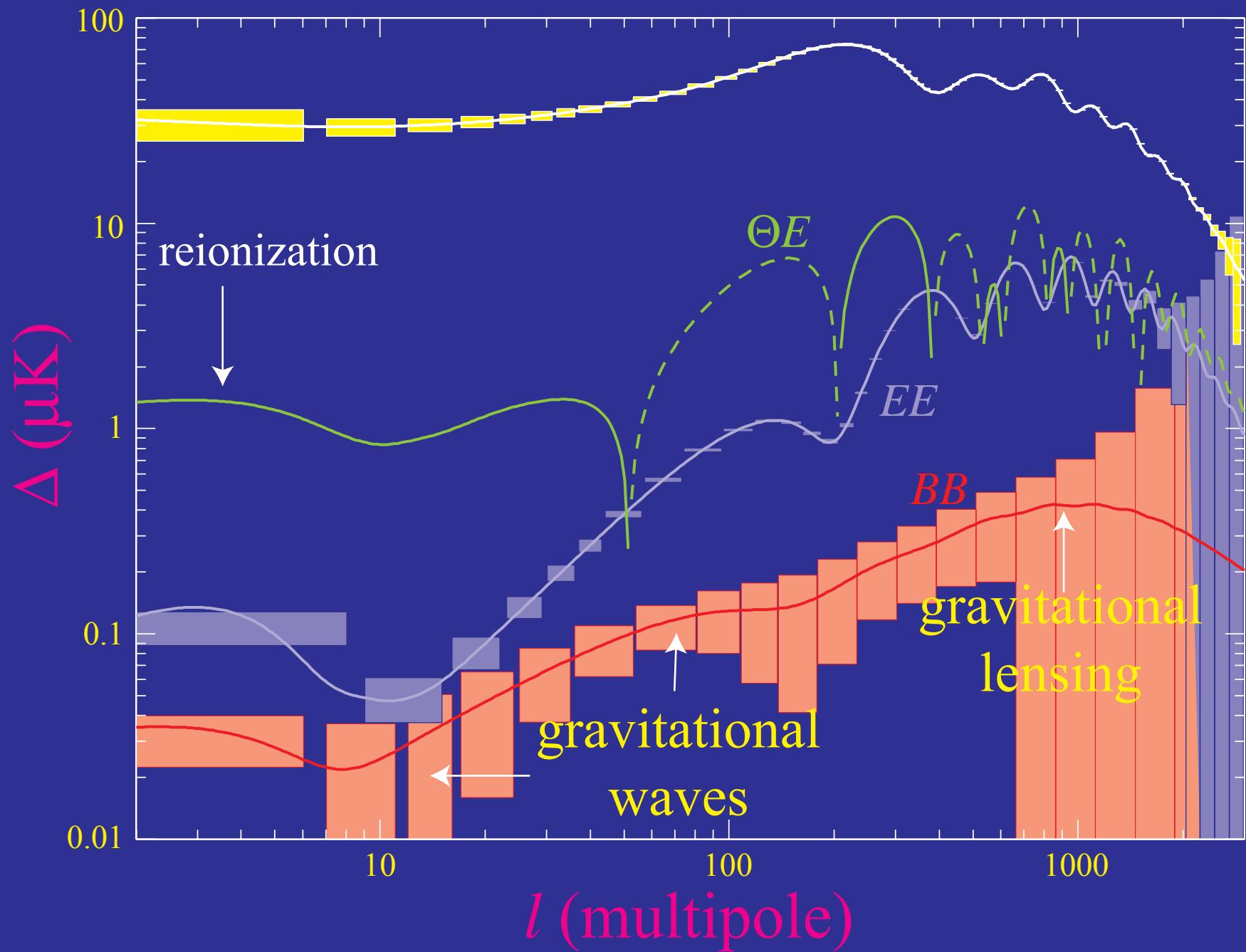


Lensed  $E$



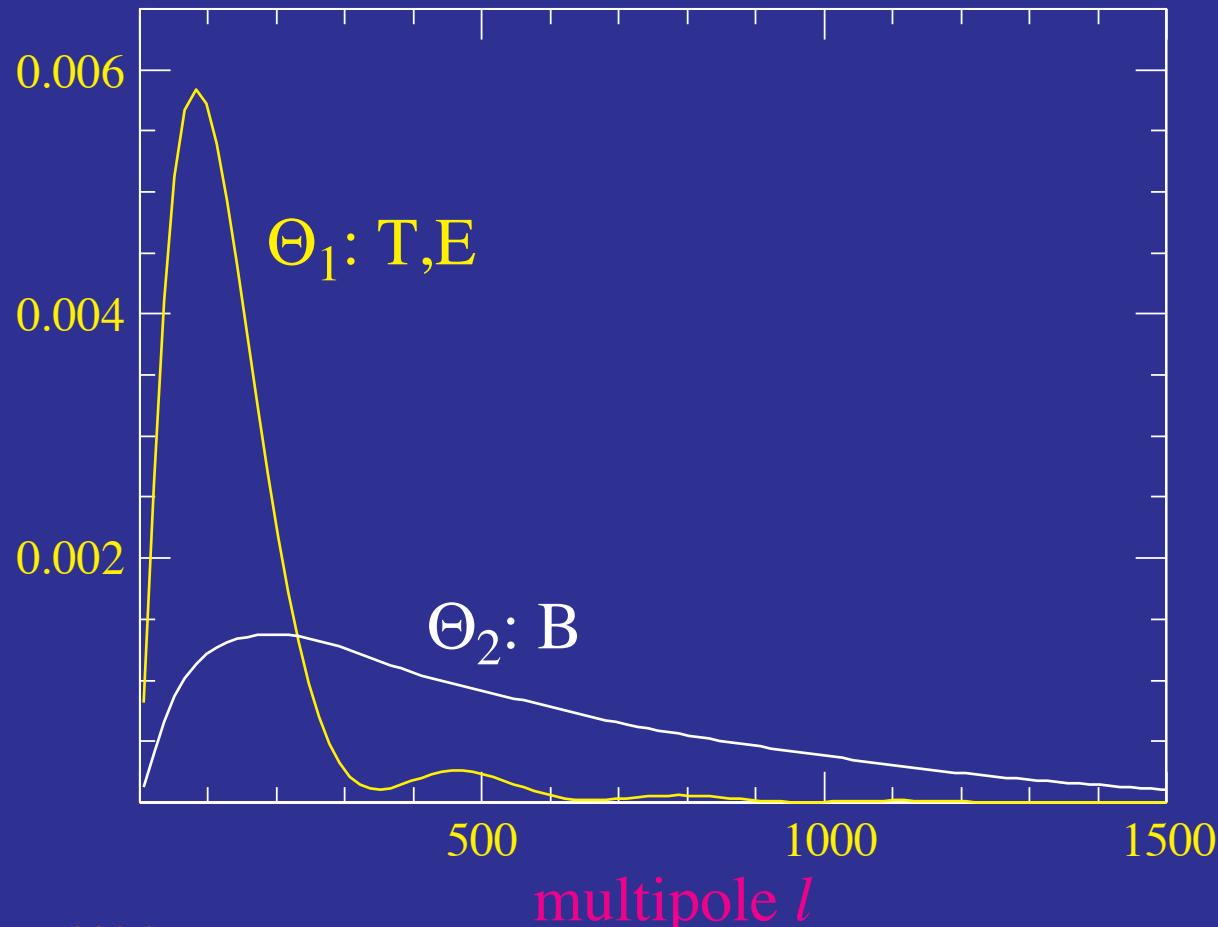
Lensed  $B$

# Power Spectrum Future



# Lensed Power Spectrum Observables

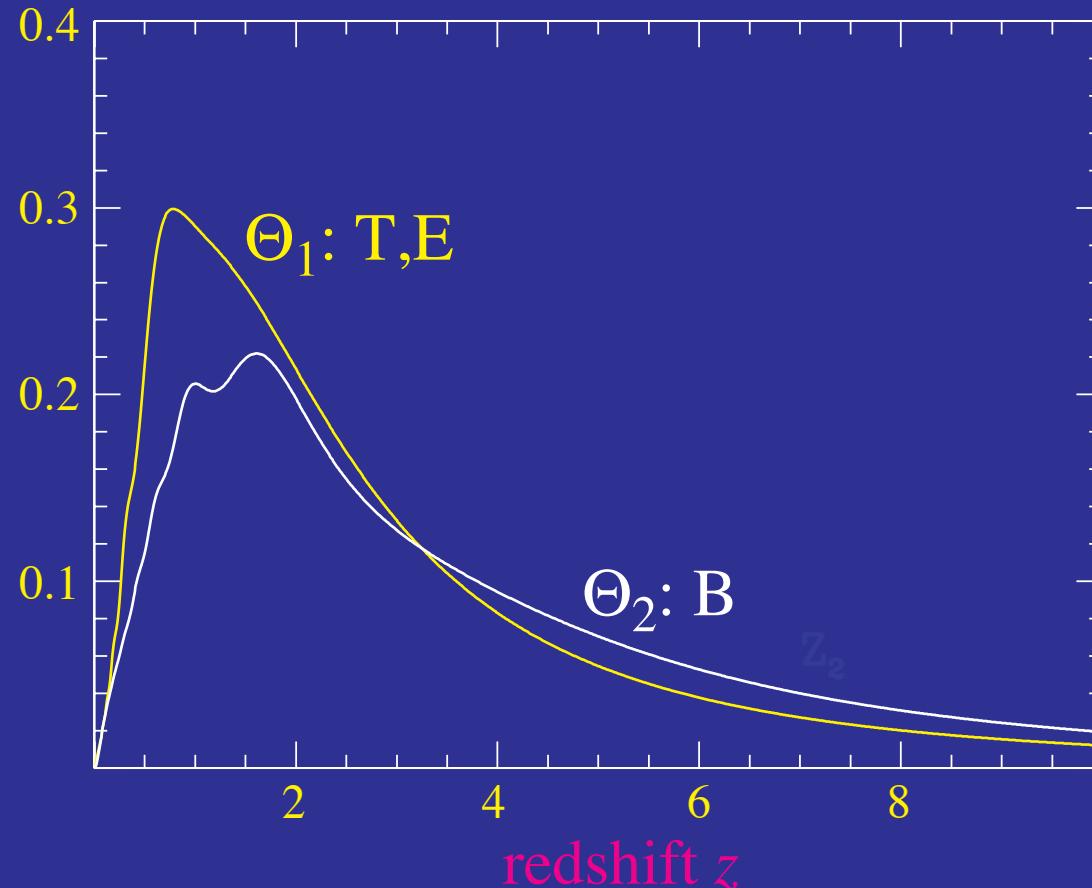
- Principal components show two observables in lensed power spectra
- Temperature and E-polarization: deflection power at  $l \sim 100$   
B-polarization: deflection power at  $l \sim 500$
- Normalized so that observables error = fractional lens power error



# Redshift Sensitivity

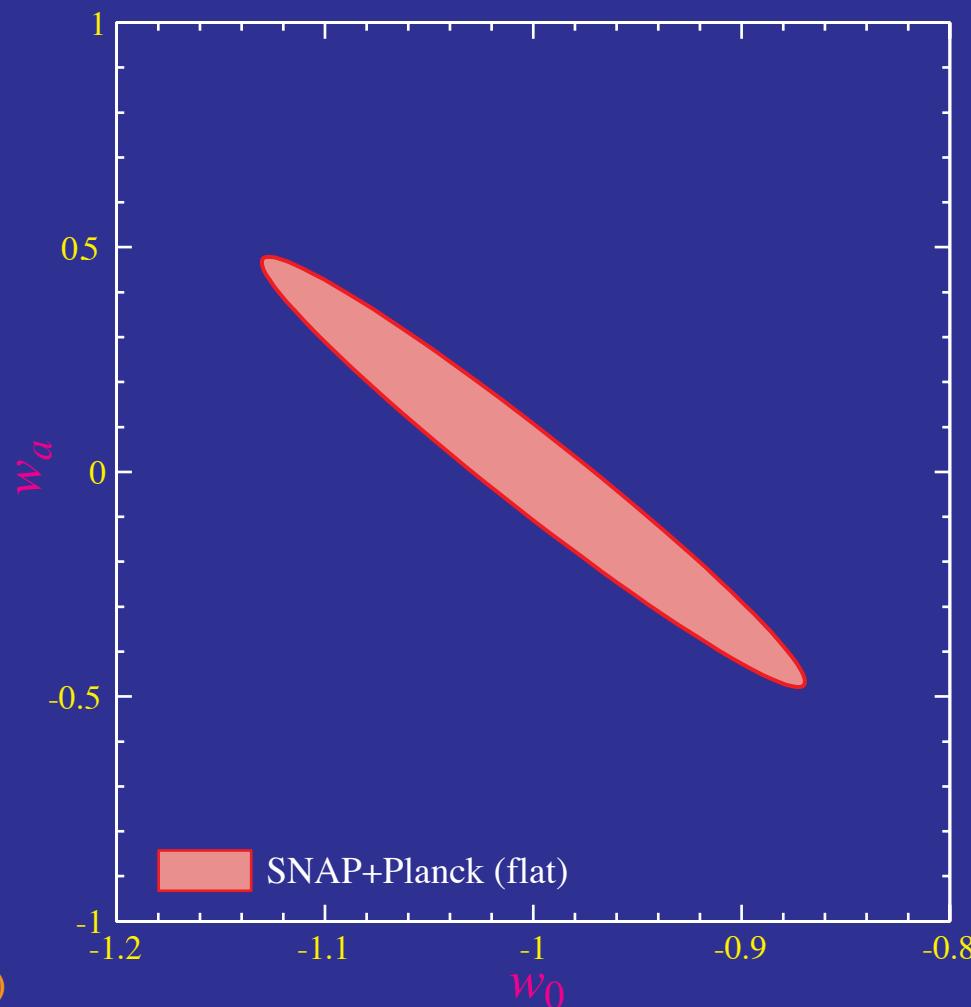
- Lensing observables probe distance and structure at high redshift

$$\frac{\delta\Theta_i}{\Theta_i} = \left[ \left( 3 - \frac{d \ln \Delta_m^2}{d \ln k} \right) \frac{\delta D_A}{D_A} - \frac{\delta H}{H} + 2 \frac{\delta G}{G} + 2 \frac{\delta D_A (D_s - D)}{D_A (D_s - D)} \right]$$



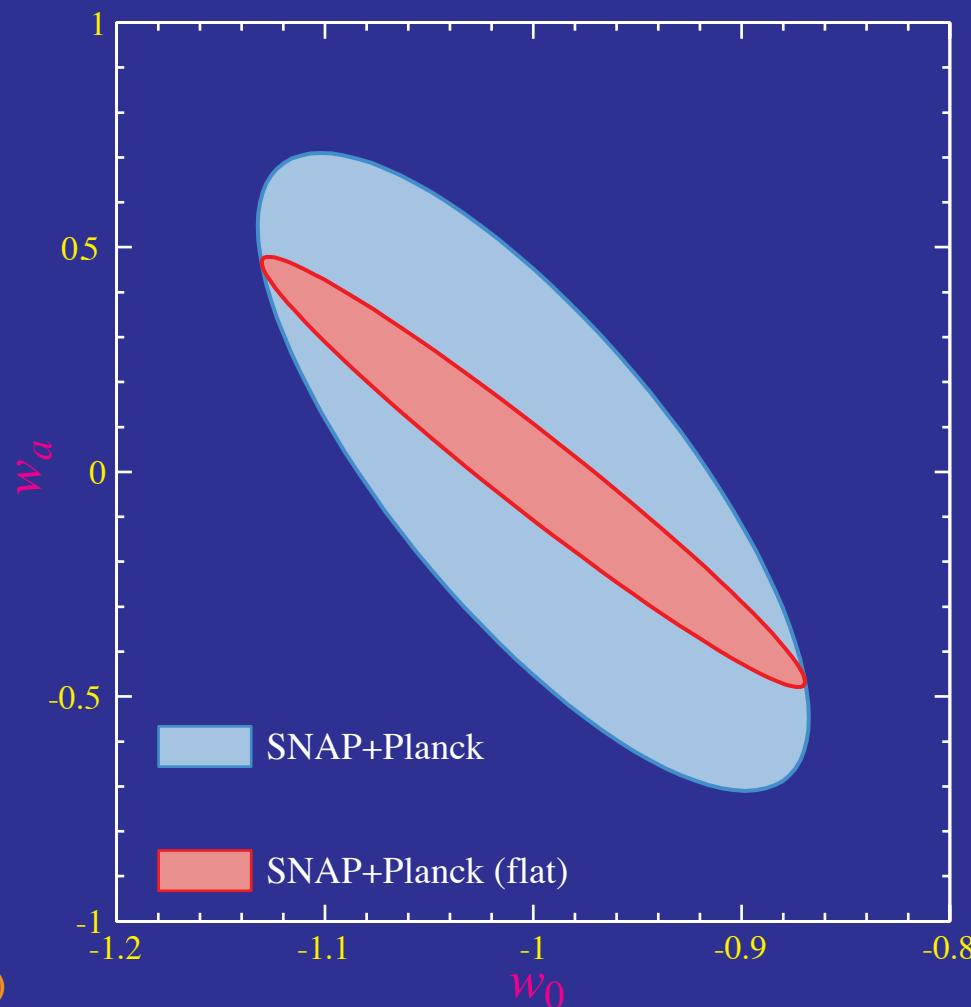
# Dark Energy Equation of State

- Marginalizing curvature degrades 68% CL area by 4.8
- CMB lensing information from SPTpol ( $\sim 3\%$  B-mode power) fully restores constraints



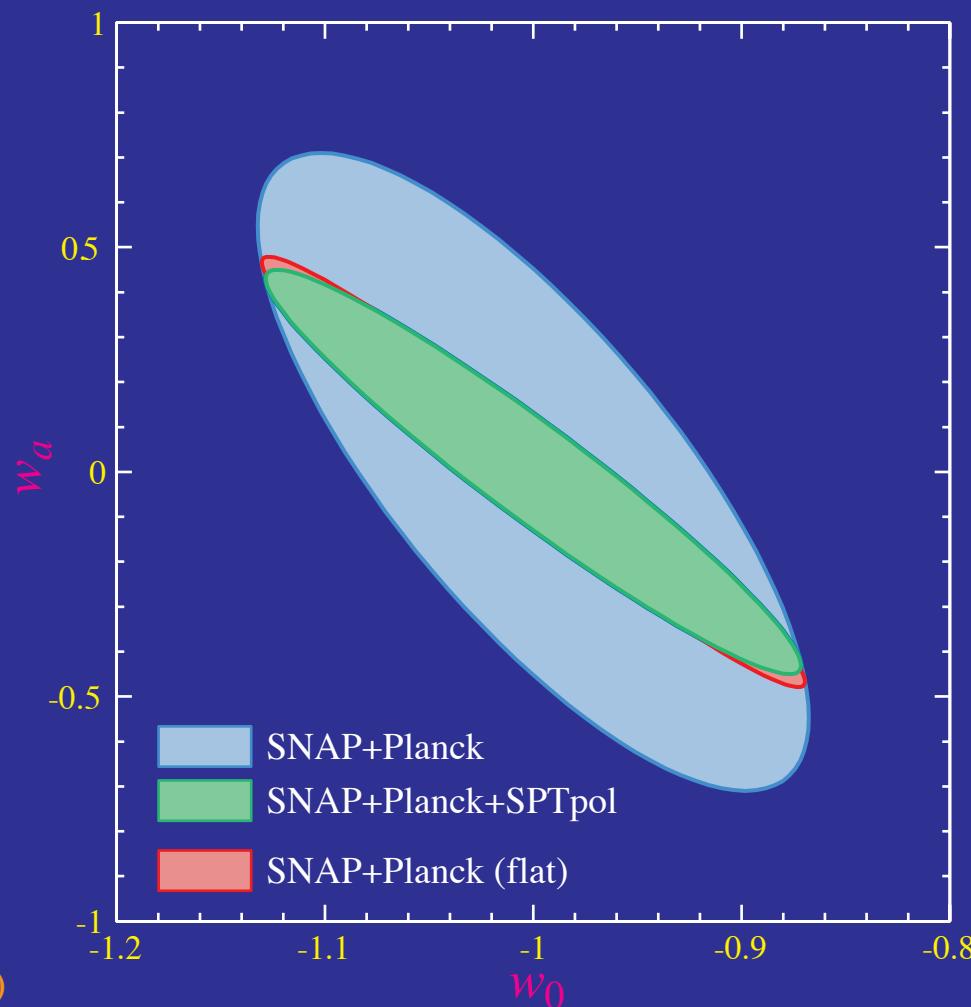
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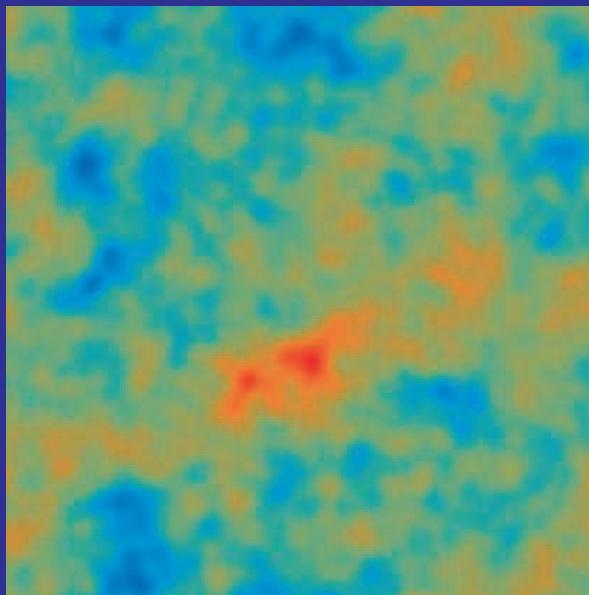
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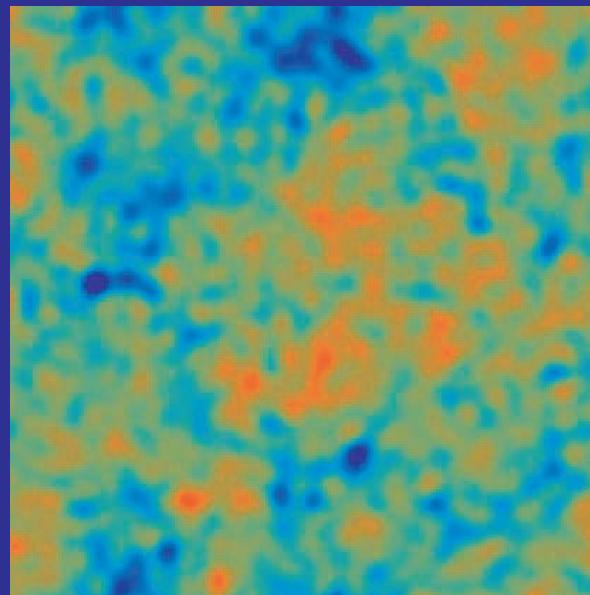


# High Signal-to-Noise B-modes

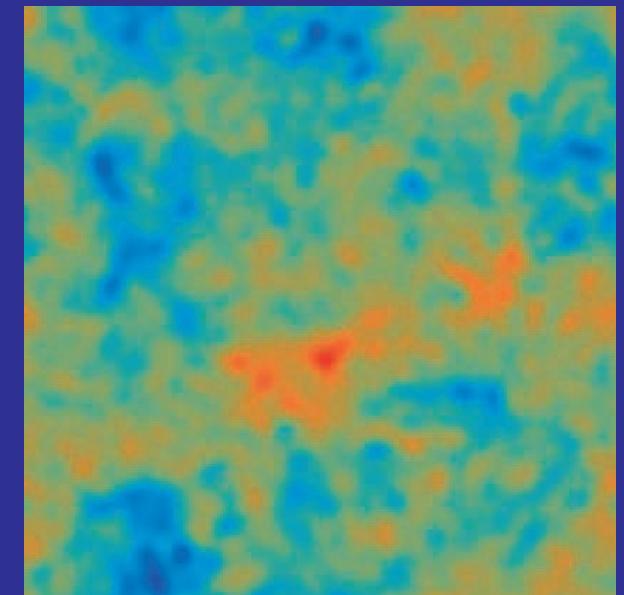
- Cosmic variance of CMB fields sets ultimate limit for  $T, E$
- $B$ -polarization allows mapping to finer scales and in principle is not limited by cosmic variance of  $E$  (Hirata & Seljak 2003)



mass



temp. reconstruction

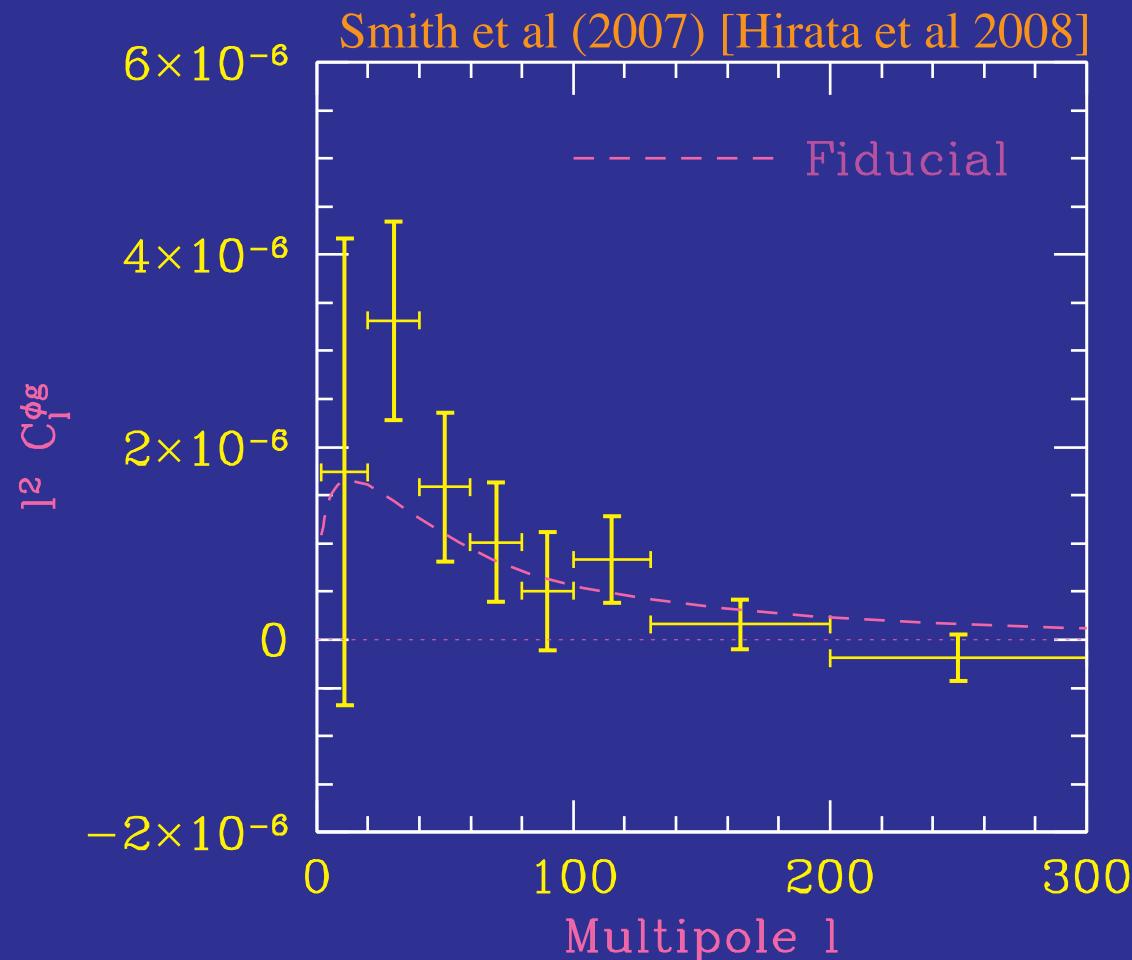


EB pol. reconstruction

100 sq. deg; 4' beam; 1 $\mu$ K-arcmin

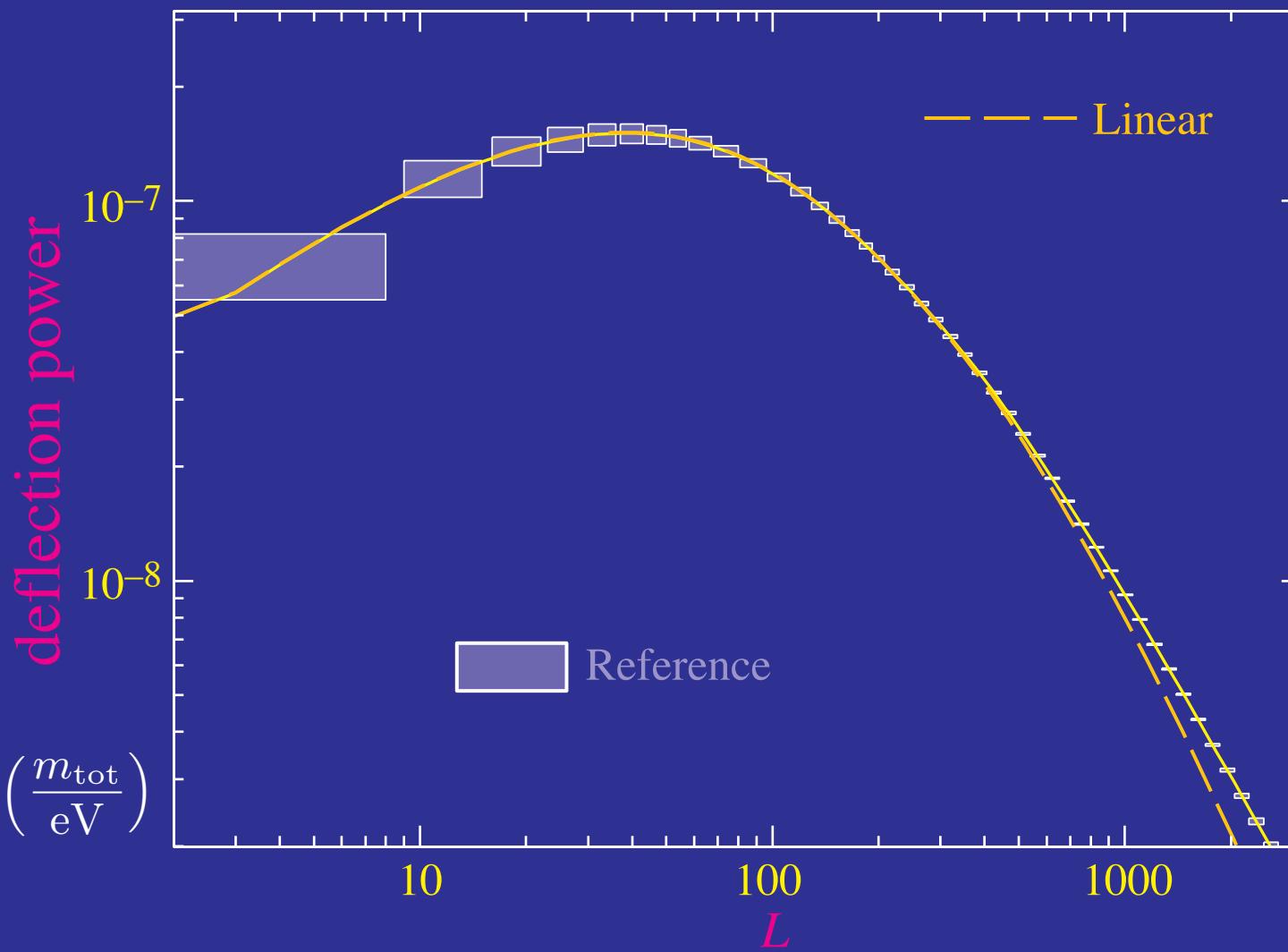
# Lensing-Galaxy Correlation

- $\sim 3\sigma+$  joint detection of WMAP lensing reconstruction with large scale structure (galaxies)
- Consistent with  $\Lambda$ CDM



# Matter Power Spectrum

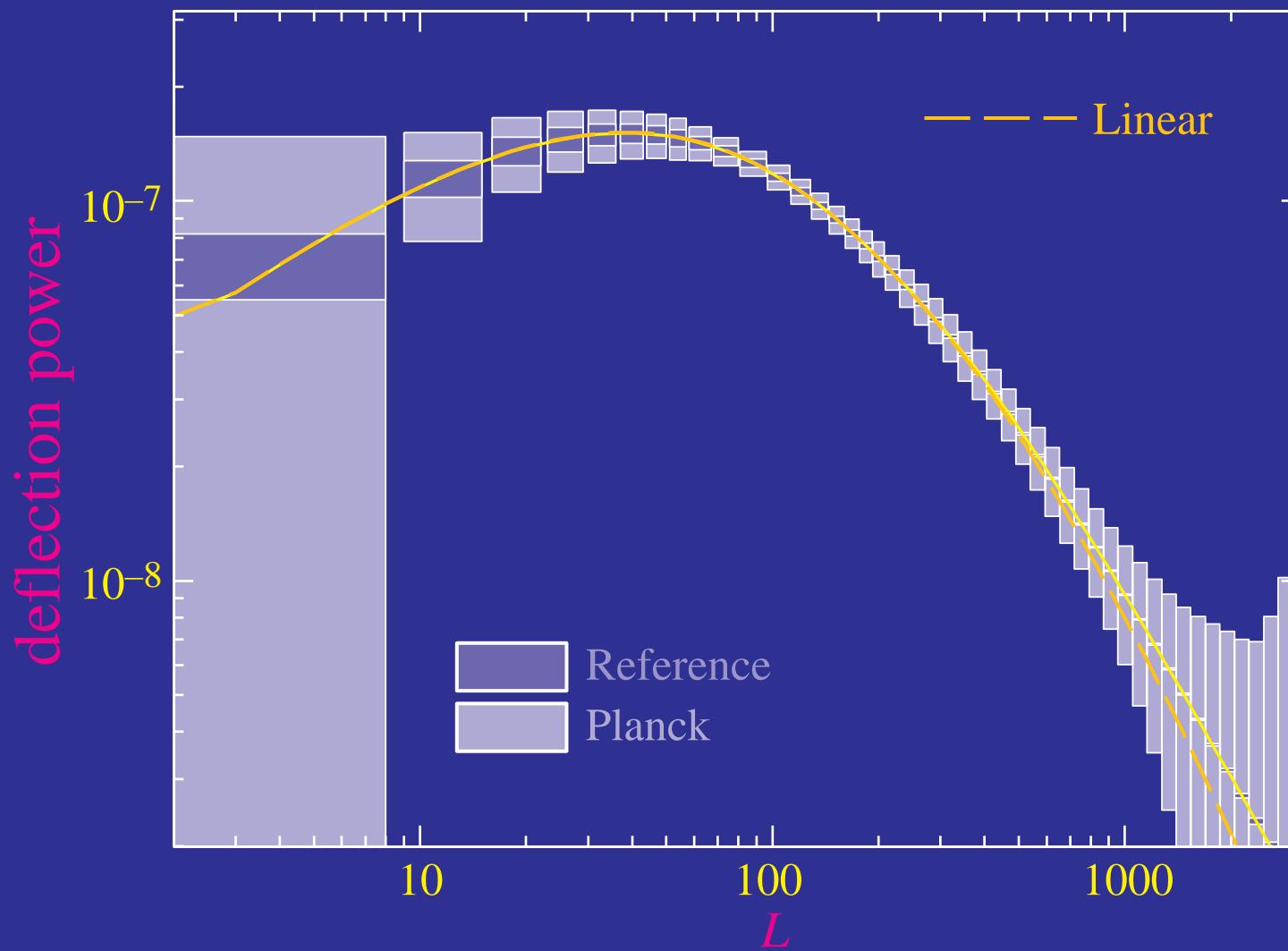
- Measuring projected matter power spectrum to cosmic variance limit across whole linear regime  $0.002 < k < 0.2 \text{ } h/\text{Mpc}$



Hu & Okamoto (2001)

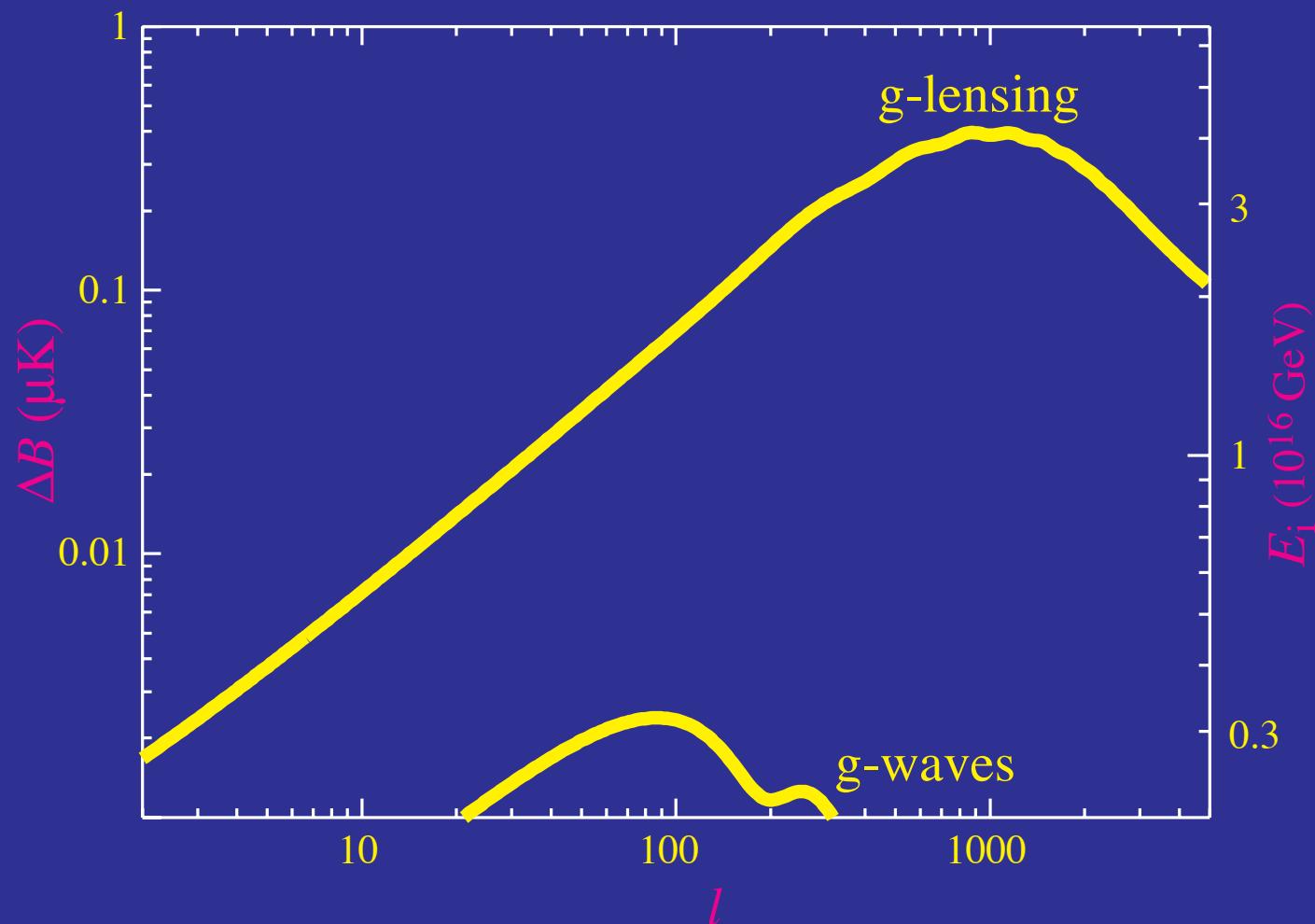
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# De-Lensing the Polarization

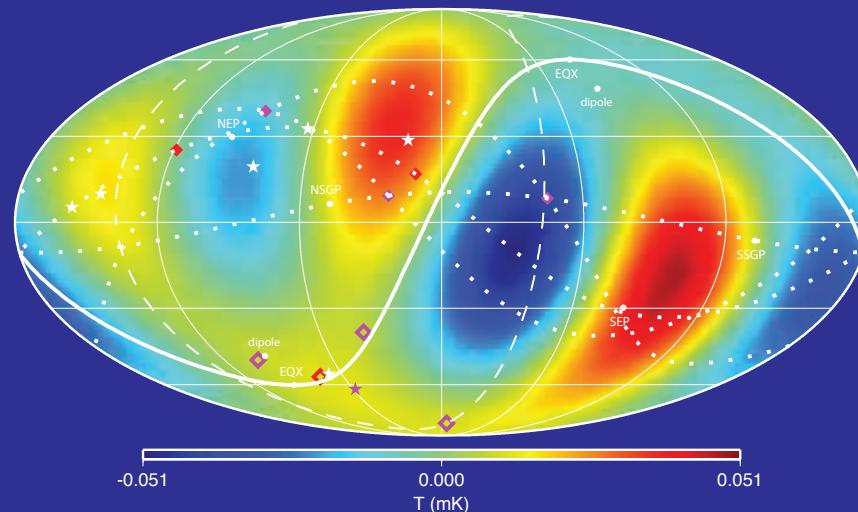
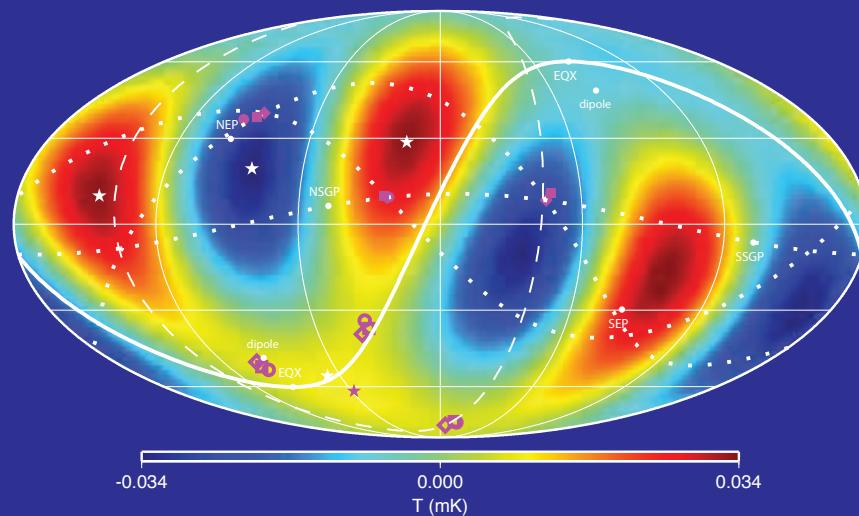
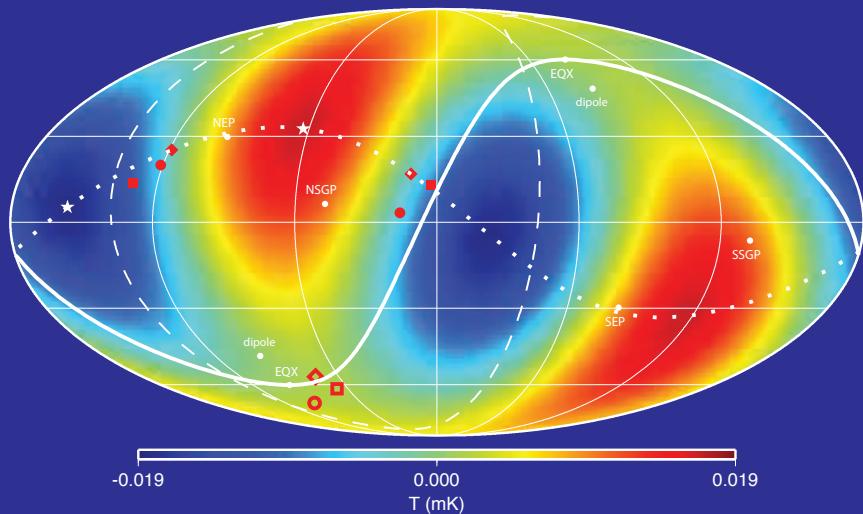
- Gravitational lensing contamination of B-modes from gravitational waves cleaned to  $E_l \sim 0.3 \times 10^{16} \text{ GeV}$   
Hu & Okamoto (2002); Knox & Song (2002); Cooray, Kedsen, Kamionkowski (2002)
- Potentially further with maximum likelihood Hirata & Seljak (2004)



# Large Scale Anomalies

# Large Angle Anomalies

- Low planar quadrupole aligned with planar octopole
- More power in south ecliptic hemisphere
- Non-Gaussian spot

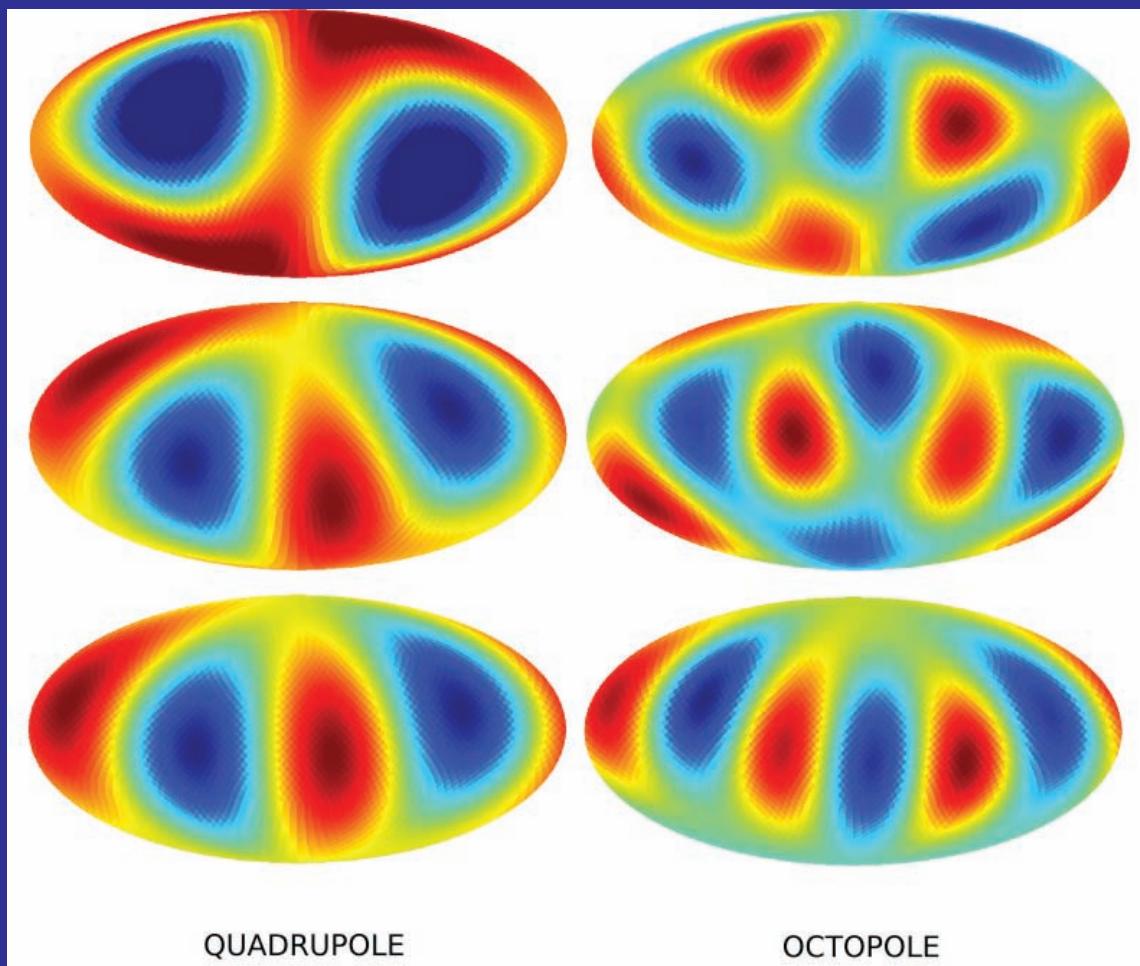


Copi et al (2006)

# Polarization Tests

- Matching polarization anomalies if cosmological

Dvorkin, Peiris, Hu (2007)



# Questions for Future

- Is the CBI excess SZ and if so is it consistent with  $\sigma_8$ ?
- Is there any evidence for primordial non-Gaussianity?
- How do we best test string-inspired ideas on inflation?
- Are large-field models where gravitational waves are observable theoretically favored?
- How much can secondary anisotropies tell us about acceleration? how far can CMB lensing constraints on dark energy, neutrinos curvature be pushed?
- What does the CMB tell us about reionization models and how can it be used in conjunction with other data?
- In practice, how much will delensing of CMB help gravitational waves? how much control on systematics and foregrounds does it require?
- What is the cause of the large scale anomalies? how do we best test ideas and explanations?