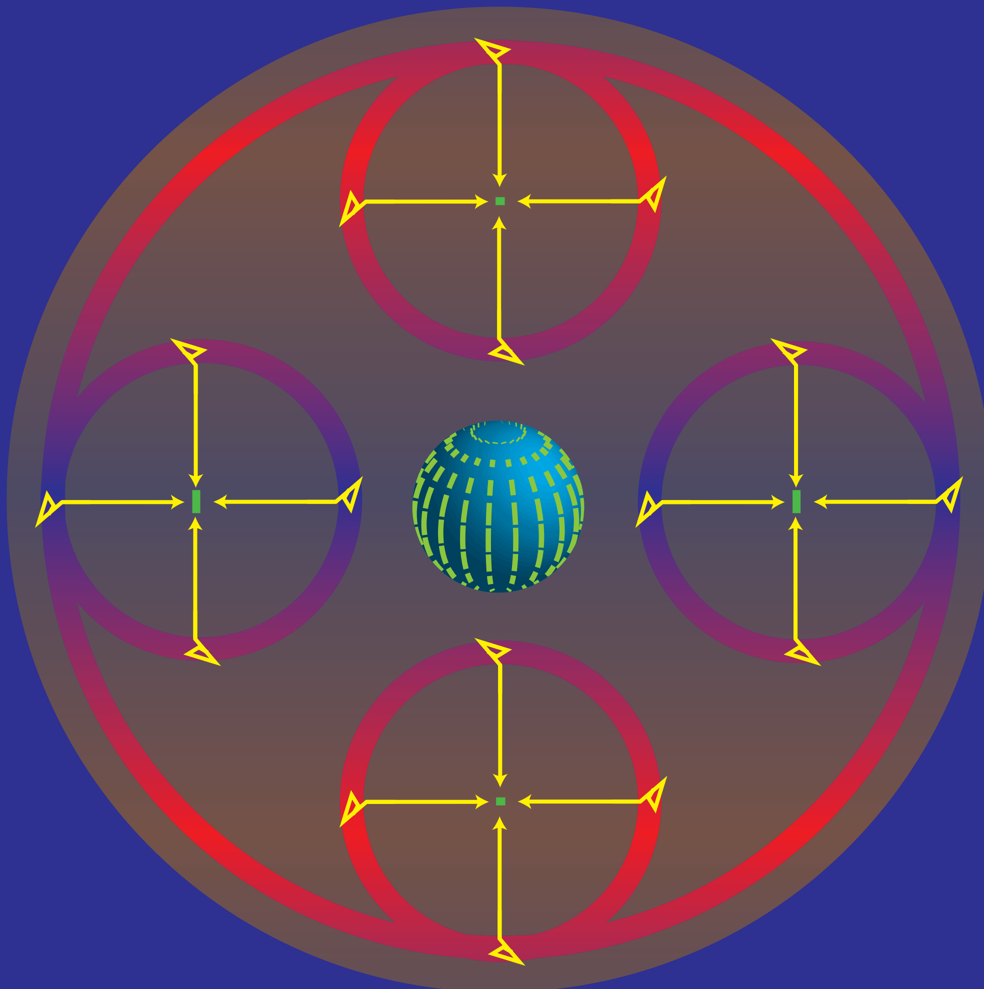
CMB Anisotropy

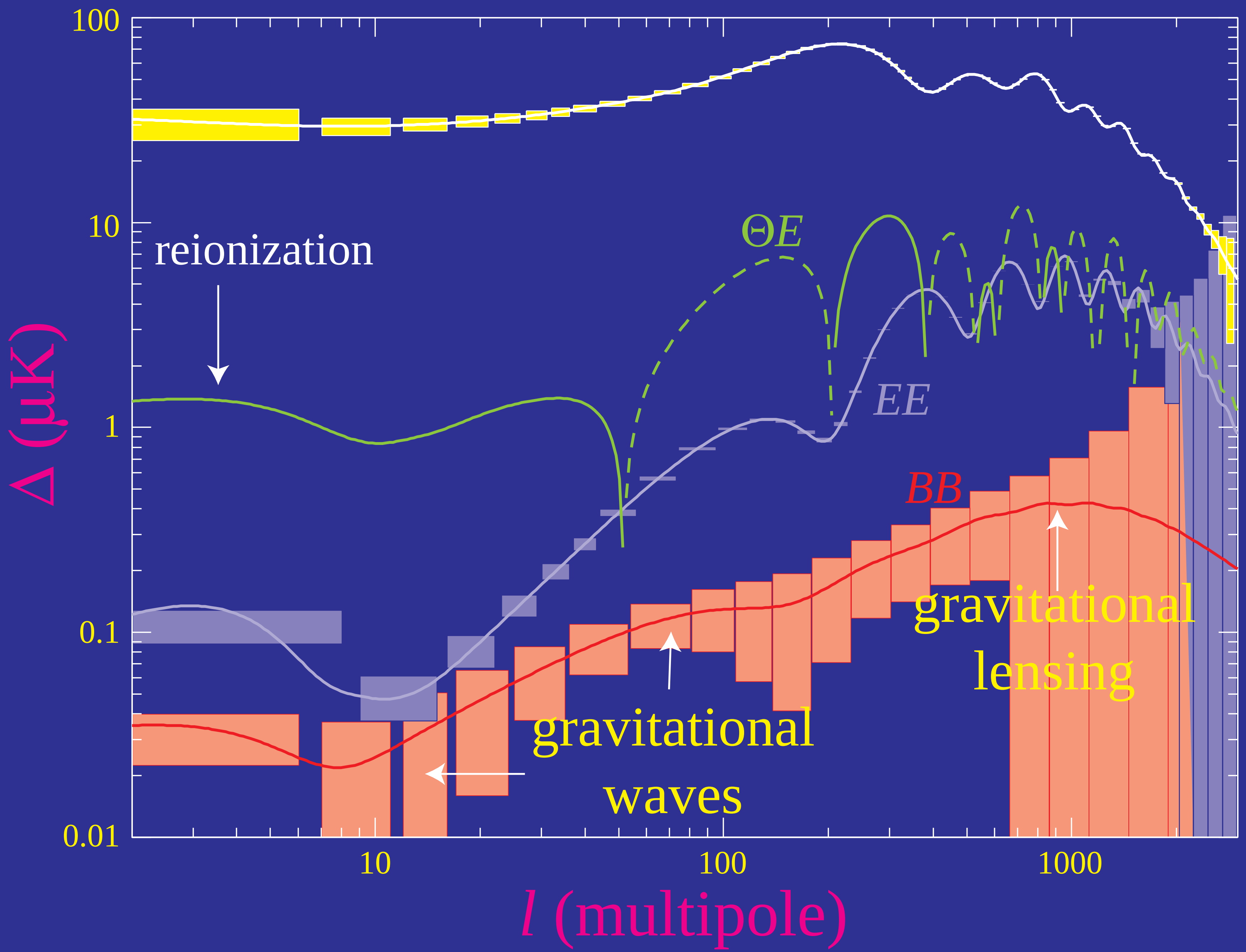


Wayne Hu

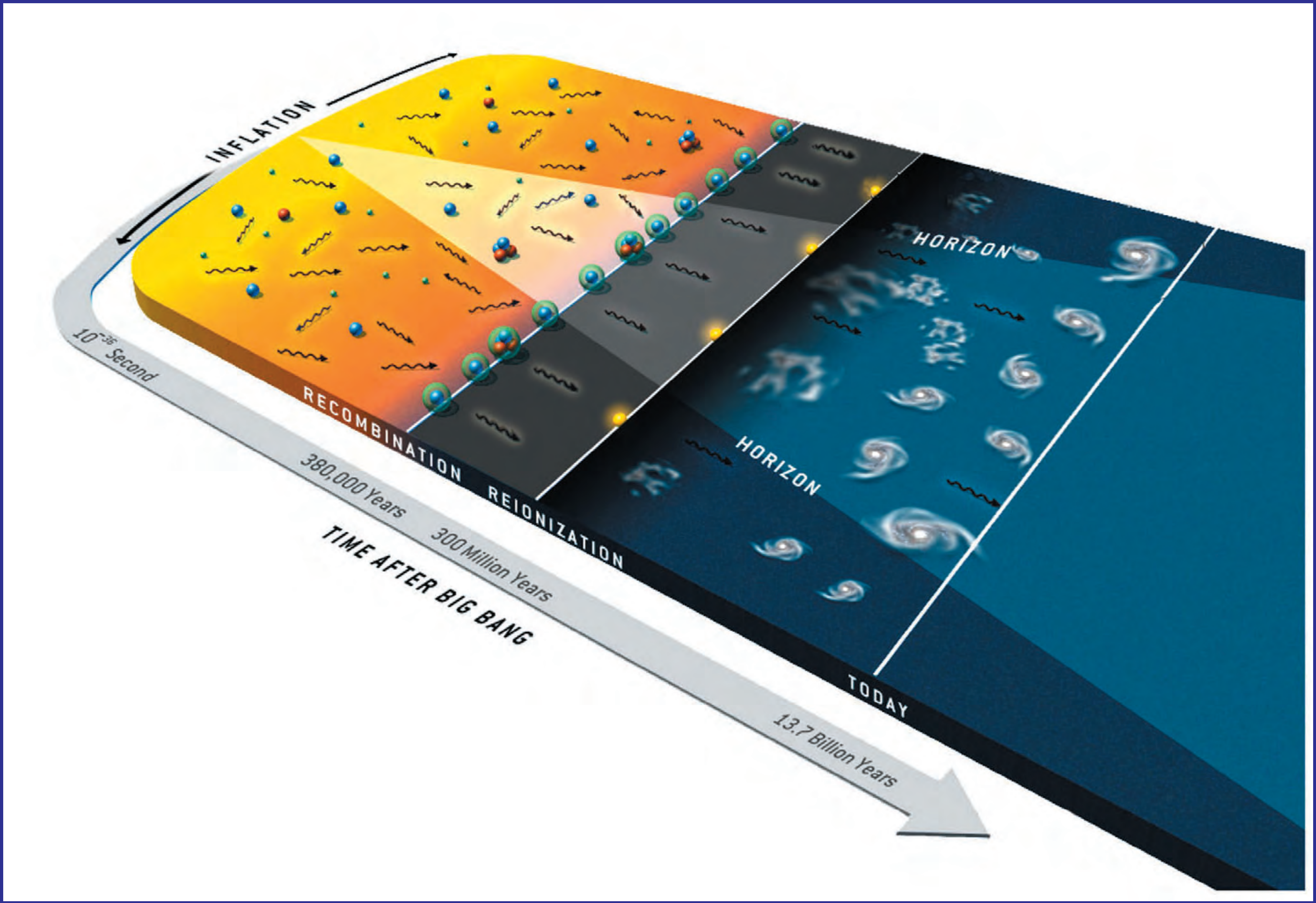
II Workshop Challenges

Campos do Jordao, December 2009

Temperature and Polarization Spectra



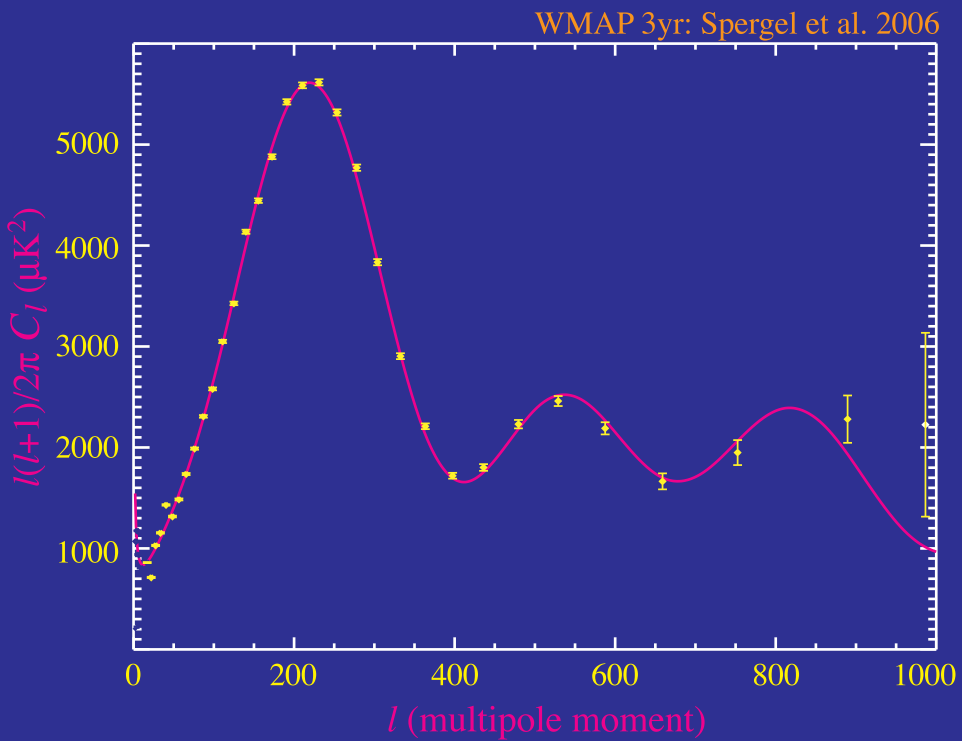
Across the Horizon

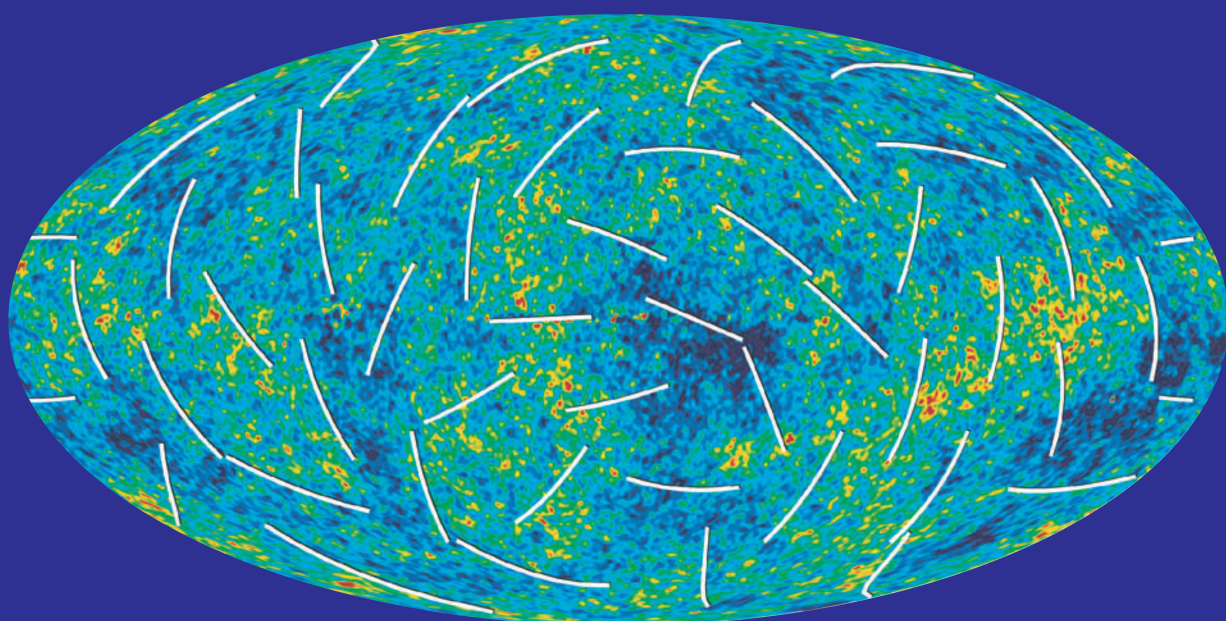


Hu & White (2004); artist:B. Christie/SciAm; available at http://background.uchicago.edu

Acoustic Oscillations

WMAP Data


WMAP 3yr: Spergel et al. 2006
5000
4000
3000
2000
1000
$l(l+1)/2\pi\, C_l\ (\mu K^2)$
0
200
400
600
800
1000
l (multipole moment)



Gravitational Ringing

- Gravitational potential wells
- Fluid falls into wells, pressure resists: acoustic oscillations

Curvature in the Power Spectrum

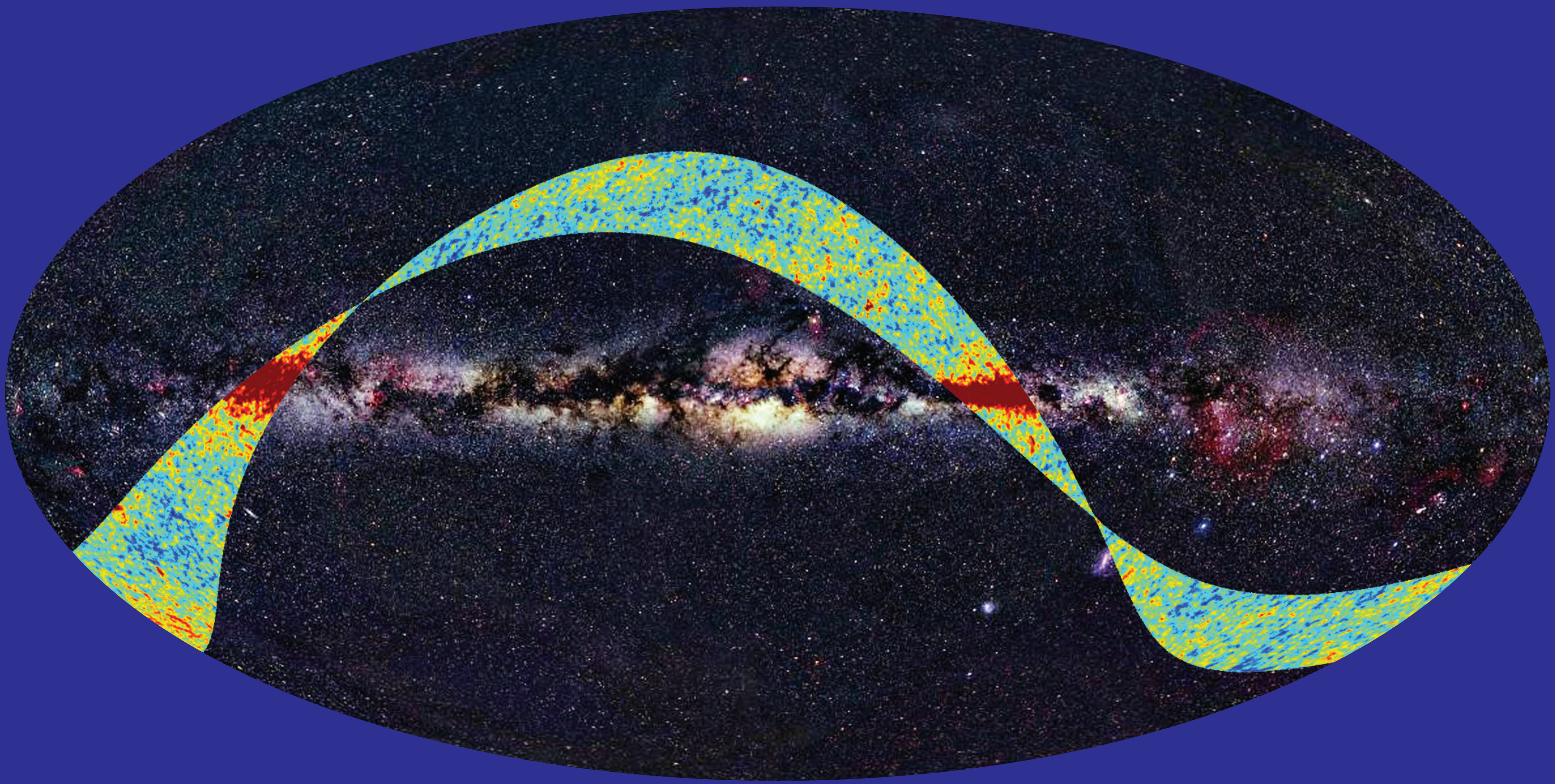
- Features scale with angular diameter distance
- Angular location of the first peak

Baryons in the Power Spectrum

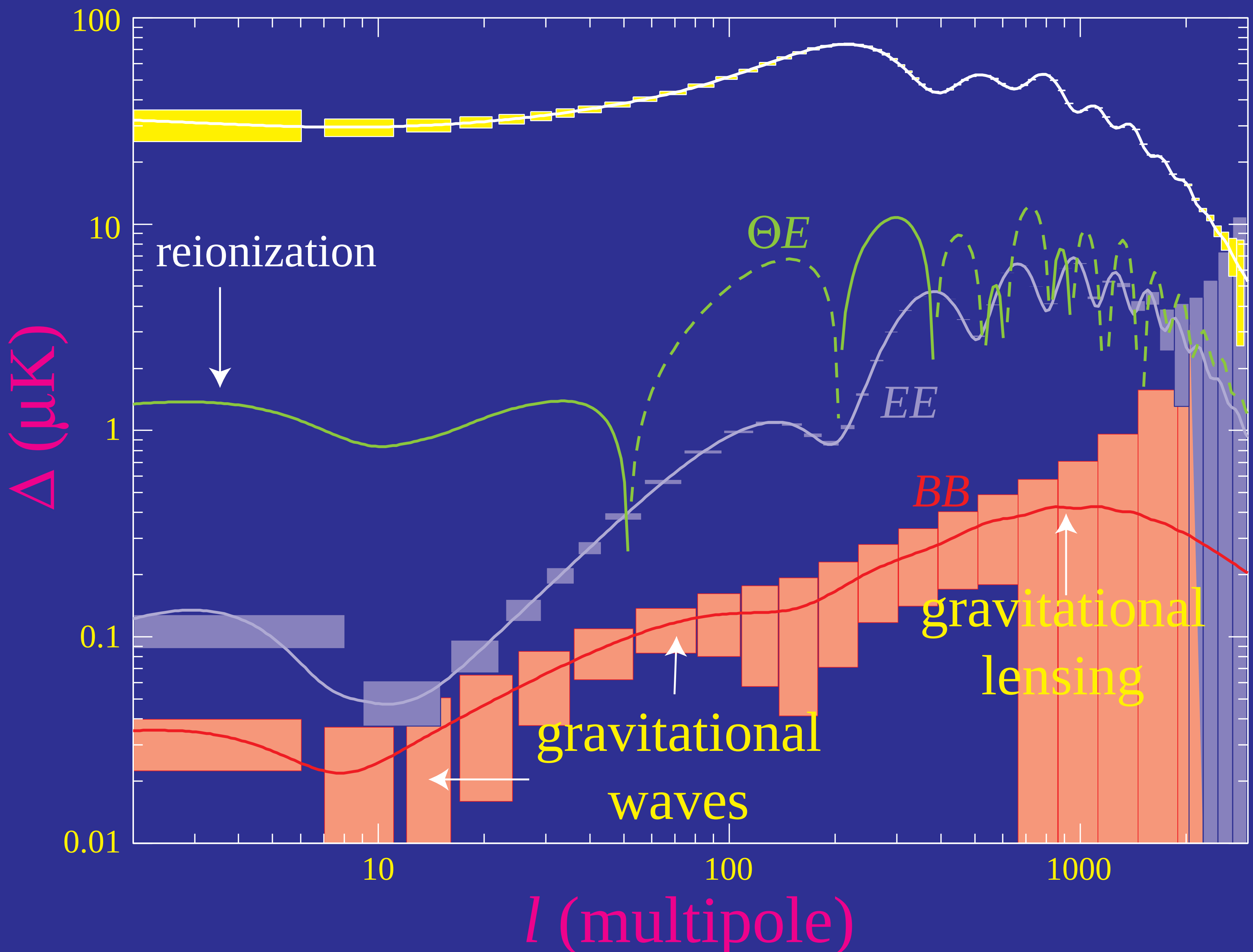
Dark Matter in the Power Spectrum

Planck First Light

- Planck satellite, first light survey



Power of Planck's Precision



Dark Energy

Fixed Deceleration Epoch

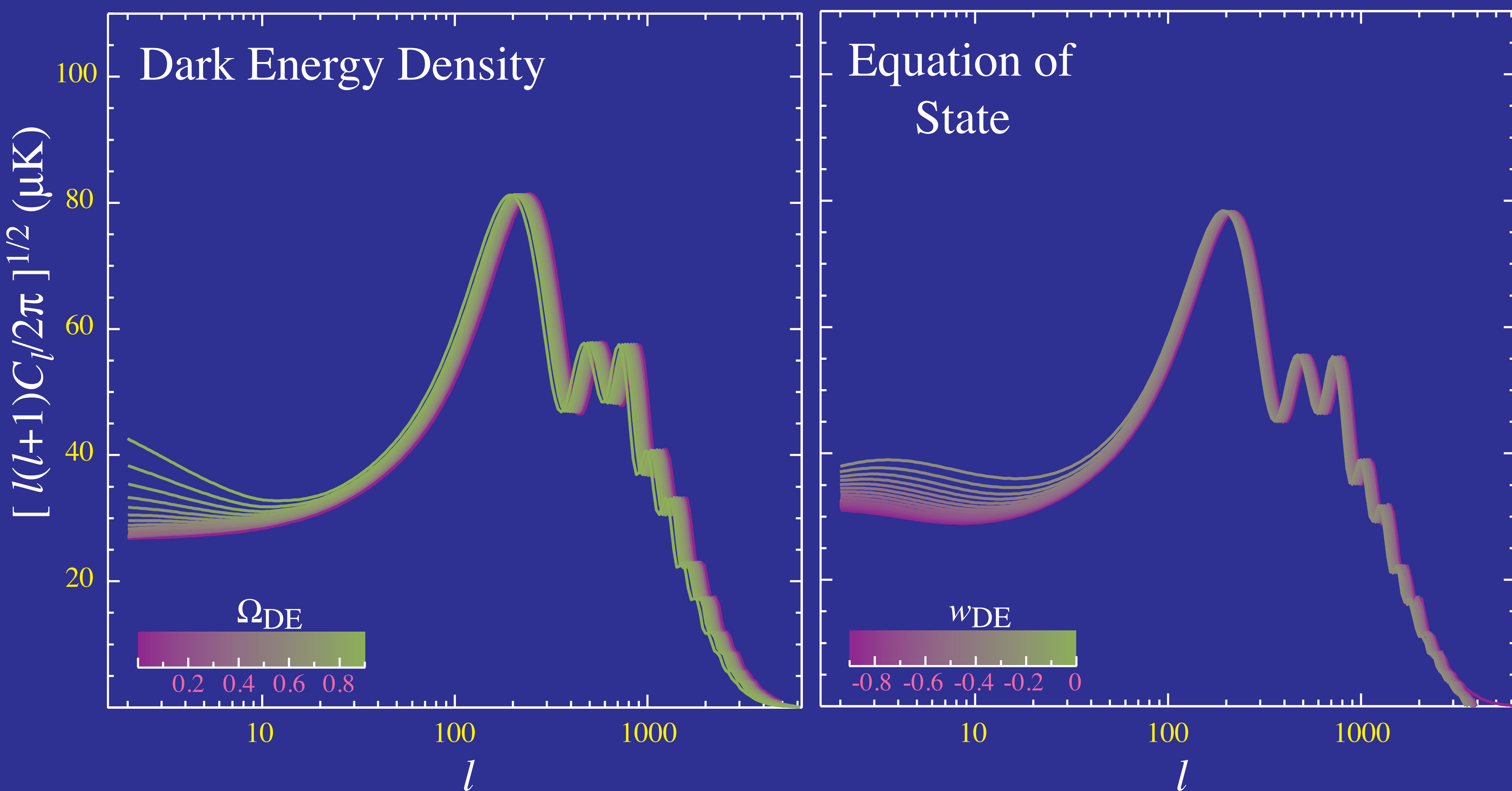
- CMB determination of matter density controls all determinations in the deceleration (matter dominated) epoch
- WMAP5: $\Omega_m h^2 = 0.1326 \pm 0.0063 \to 5\%$
- Distance to recombination D_* determined to $\frac{1}{4}5\% \approx 1.25\%$
- Expansion rate during any redshift in the deceleration epoch determined to 5%
- Distance to any redshift in the deceleration epoch determined as

$$D(z) = D_* - \int_z^{z_*} \frac{dz}{H(z)}$$

- Volumes determined by a combination $dV = D_A^2 d\Omega dz / H(z)$
- Structure also determined by growth of fluctuations from z_*
- $\Omega_m h^2$ can be determined to $\sim 1\%$ from Planck.

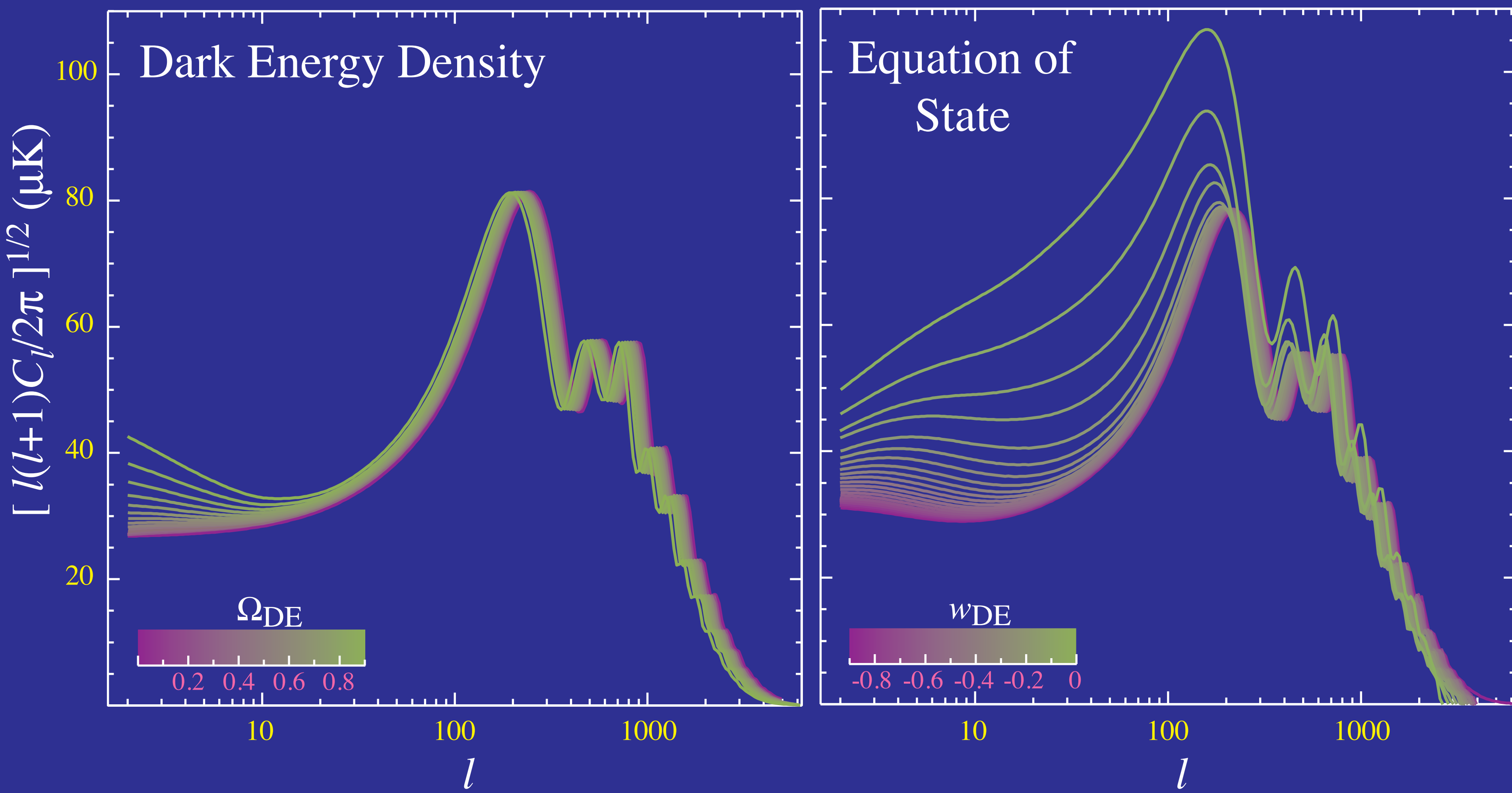
Dark Energy

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



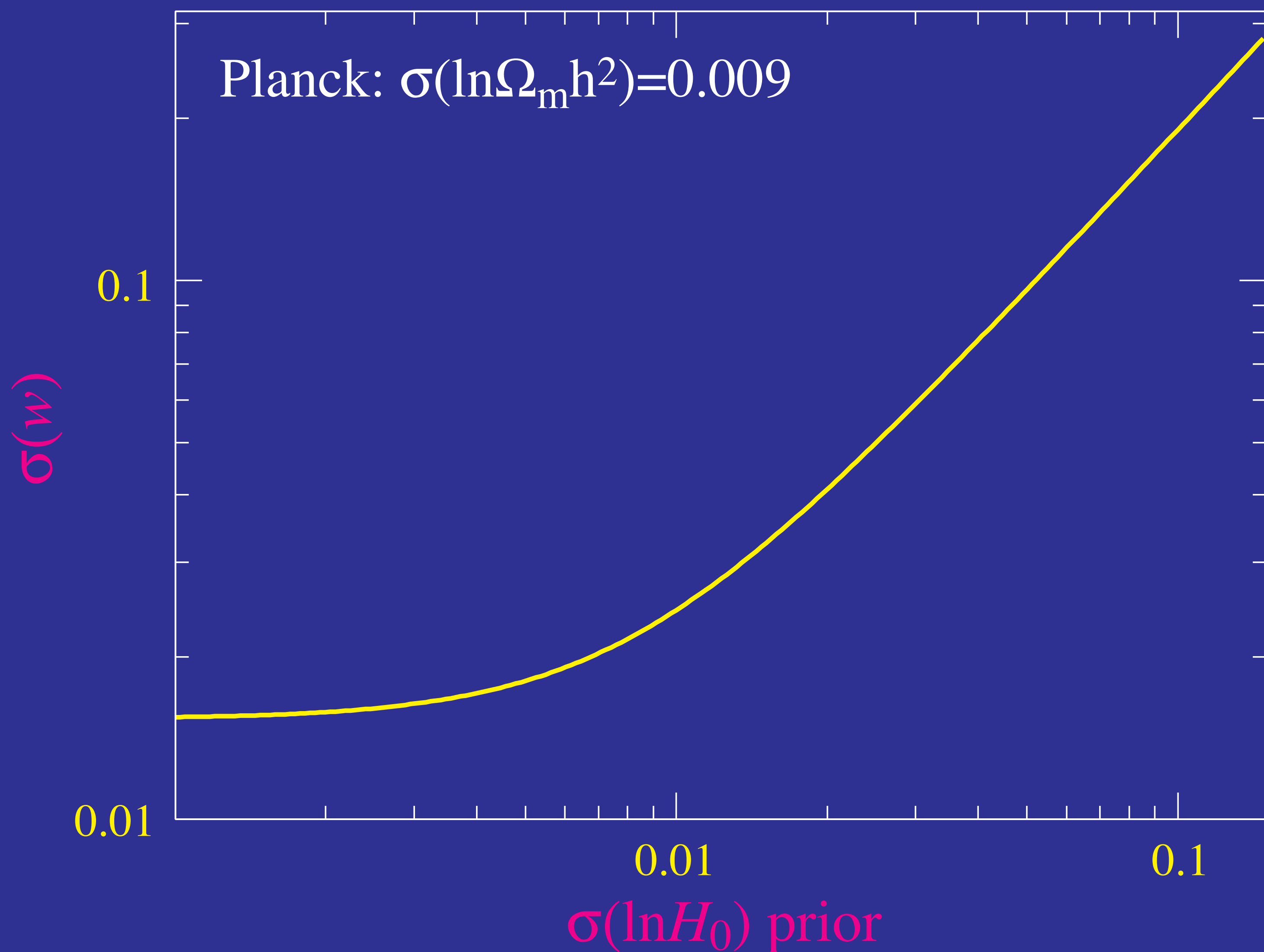
Dark Energy

- Peaks measure distance to recombination
- ISW effect constrains dynamics of acceleration and early dark energy



Forecasts for CMB+H_0

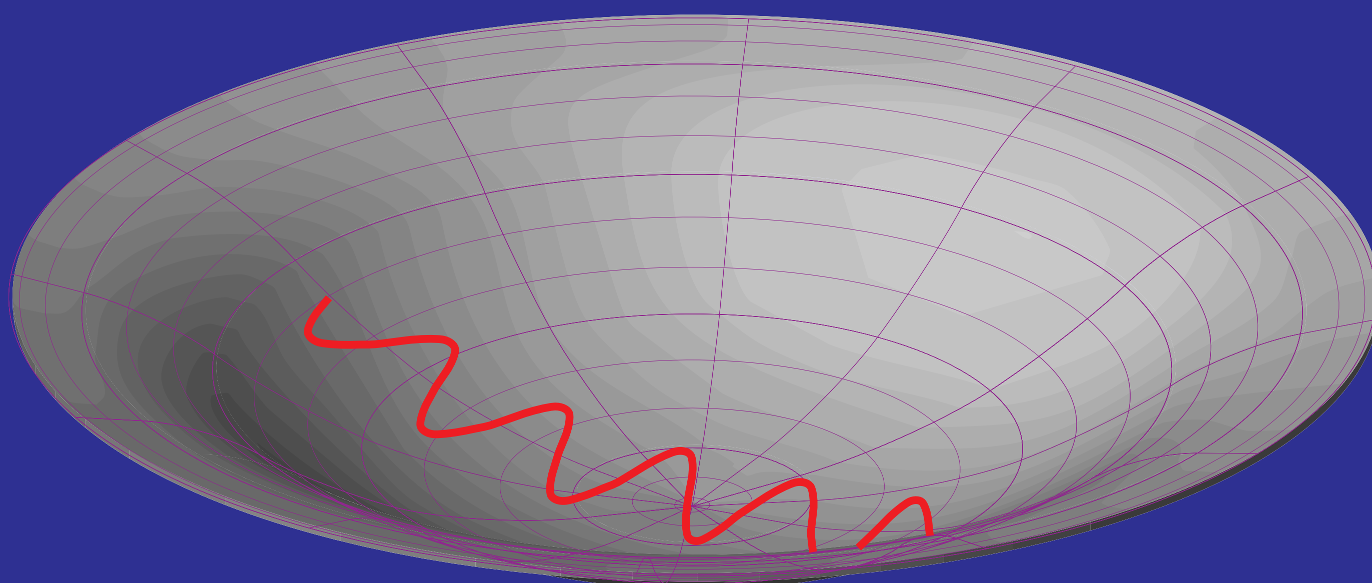
- To complement CMB observations with $\Omega_m h^2$ to 1%, an H_0 of ~1% enables constant w measurement to ~2% in a flat universe



Hu (2004)

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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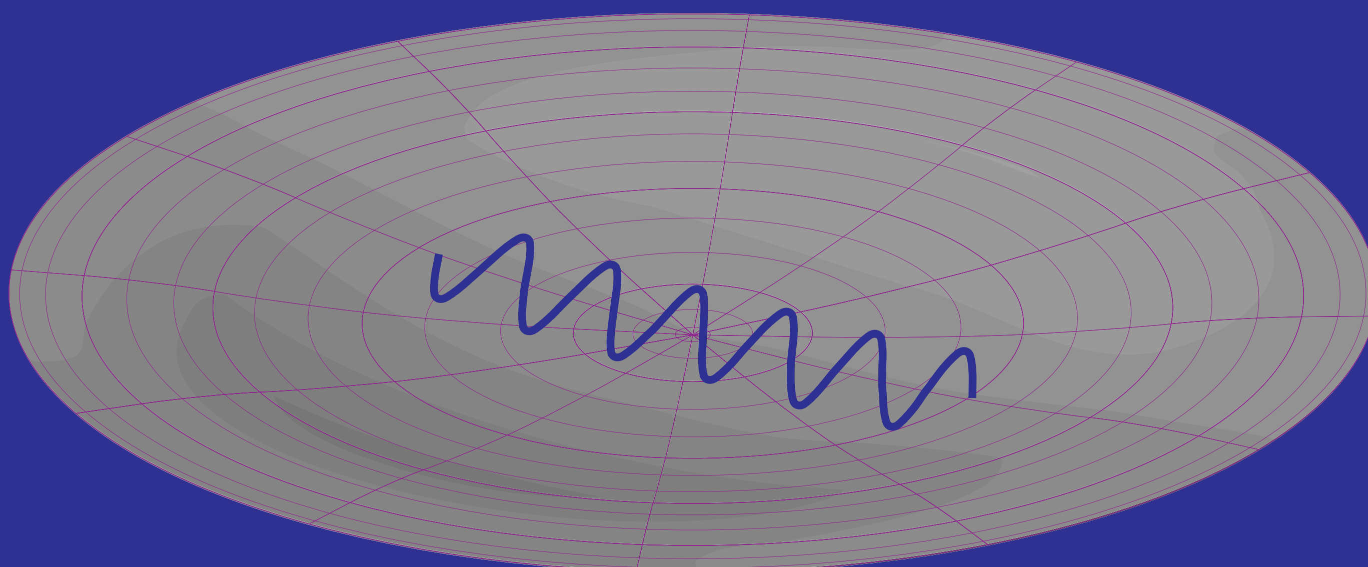
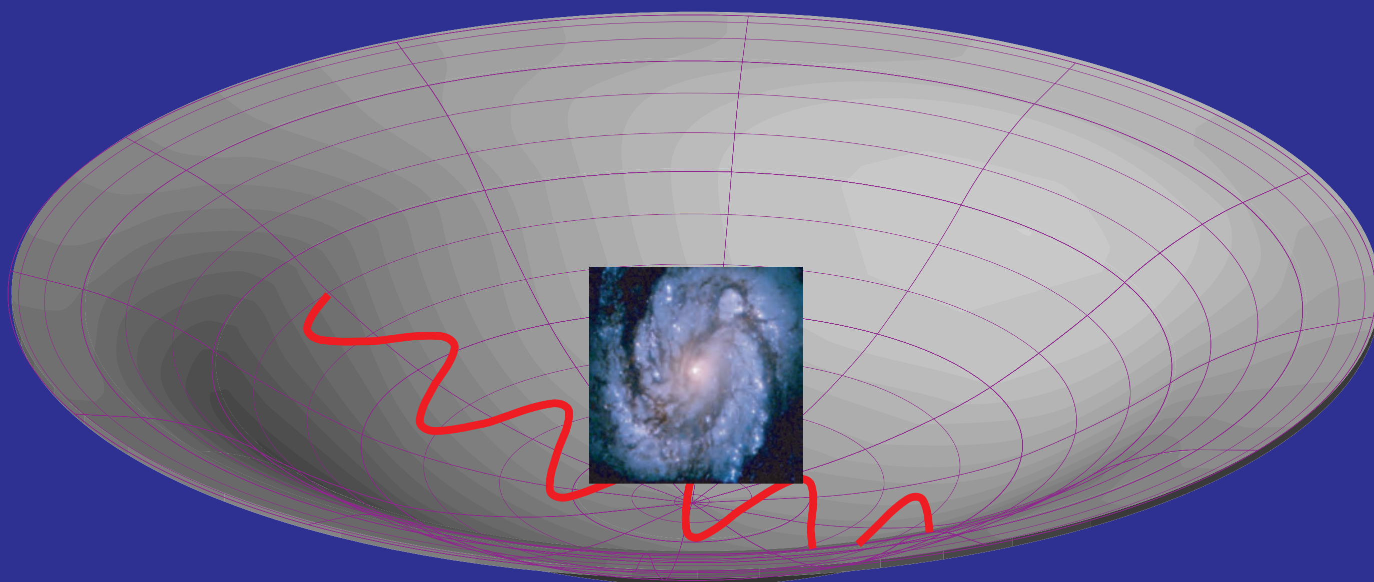


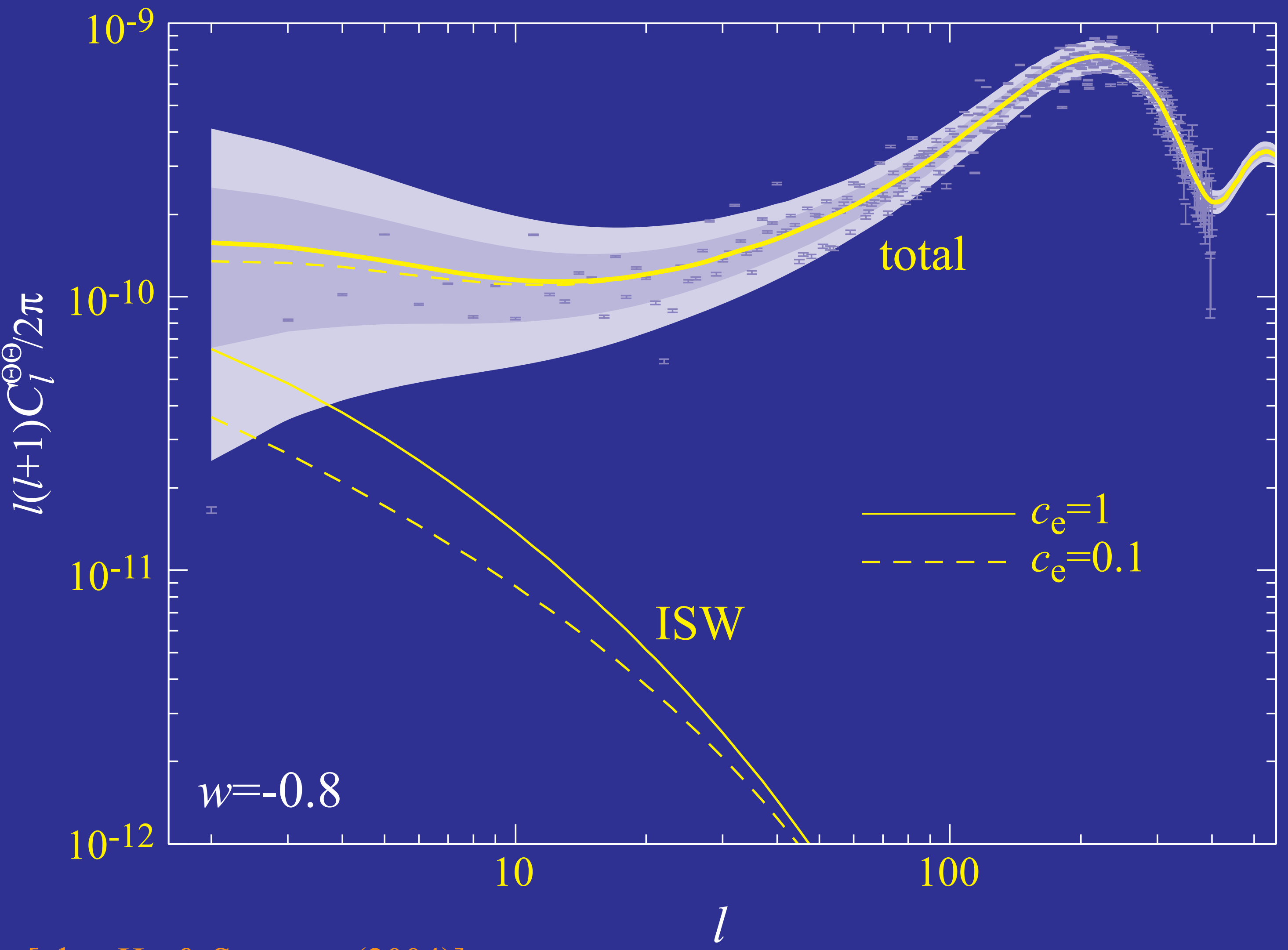
ISW-Galaxy Correlation

- Decaying potential: galaxy positions correlated with CMB
- Growing potential: galaxy positions anticorrelated with CMB
- Observations indicate correlation



Dark Energy Clustering

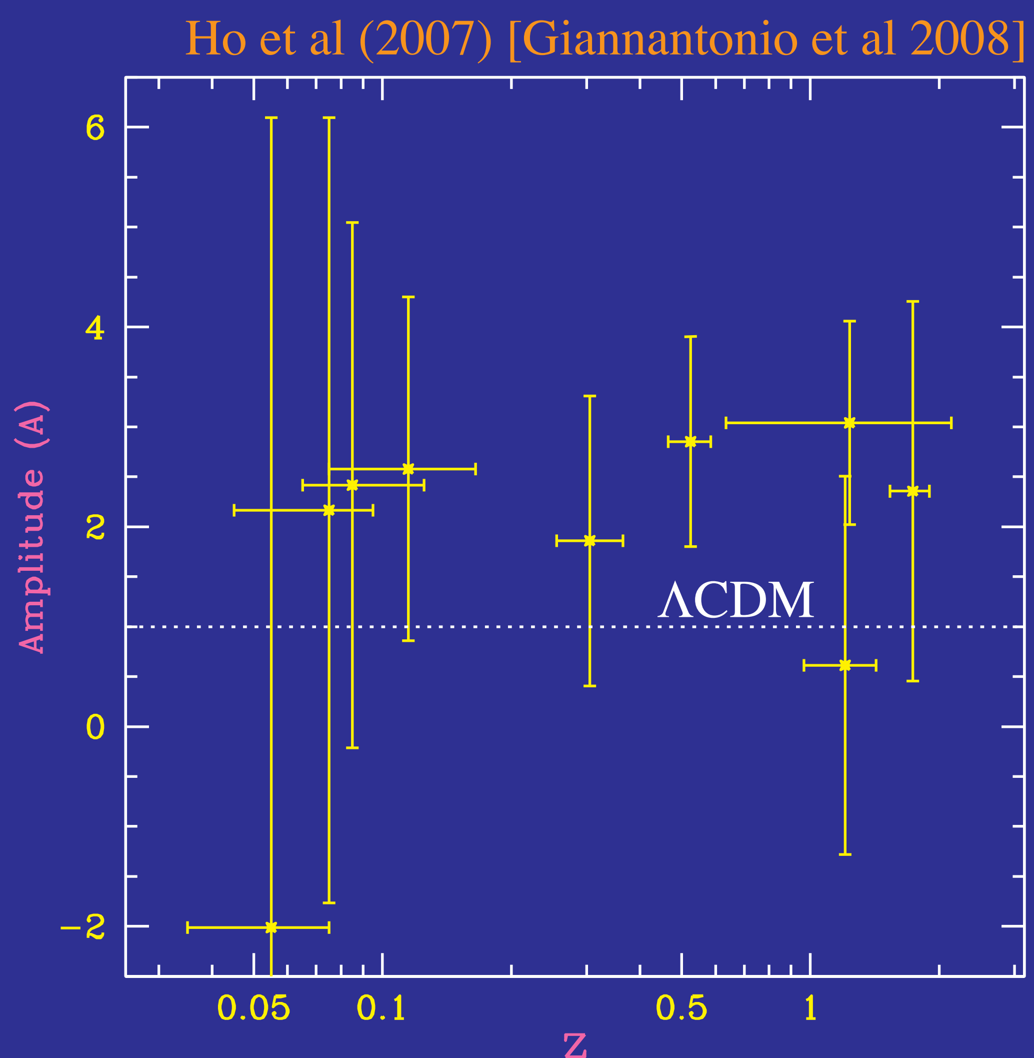
- ISW effect intrinsically sensitive to dark energy smoothness
- Large angle contributions reduced if clustered



Hu (1998); [plot: Hu & Scranton (2004)]

ISW-Galaxy Correlation

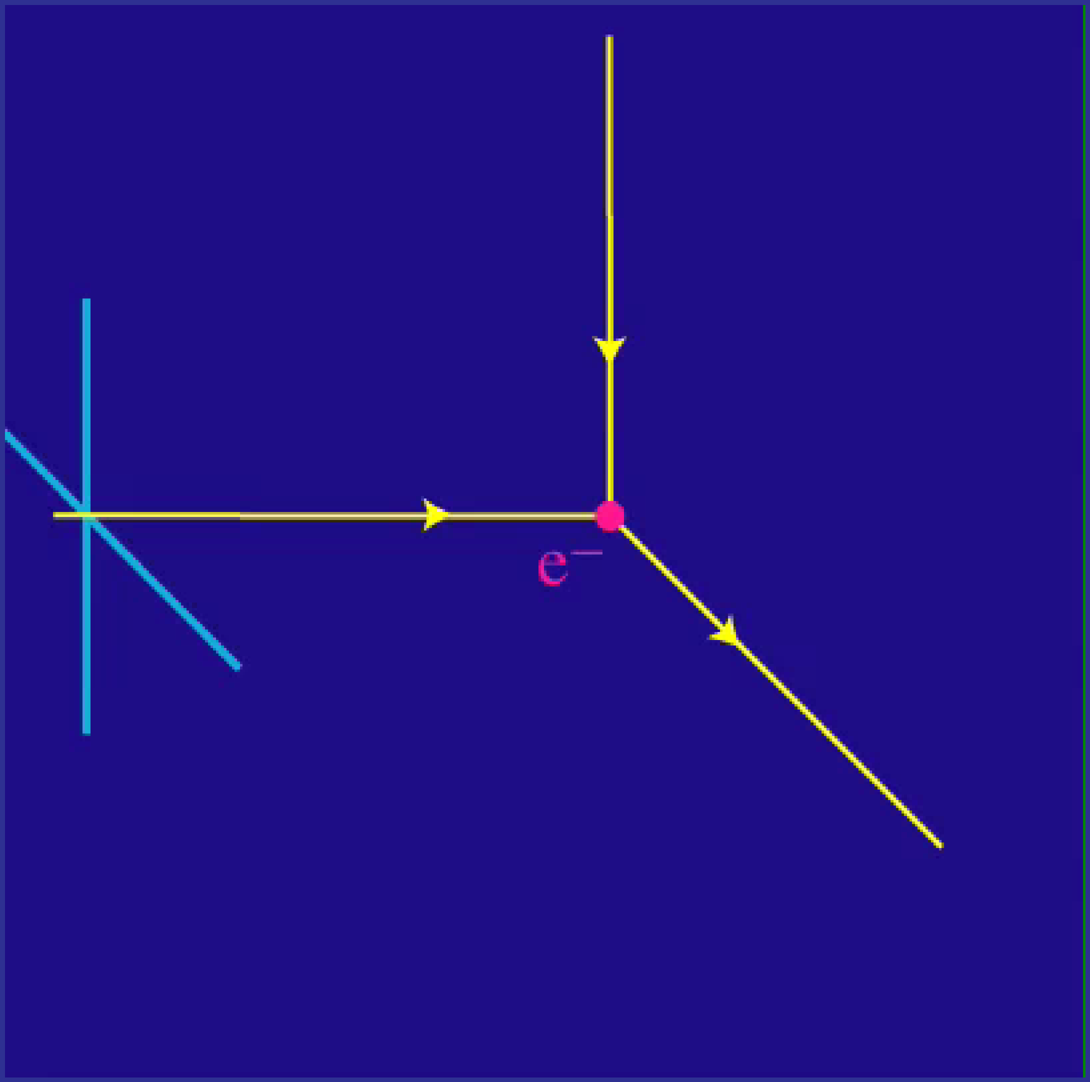
- ~4σ joint detection of ISW correlation with large scale structure (galaxies)
- ~2σ high compared with ΛCDM



Polarization

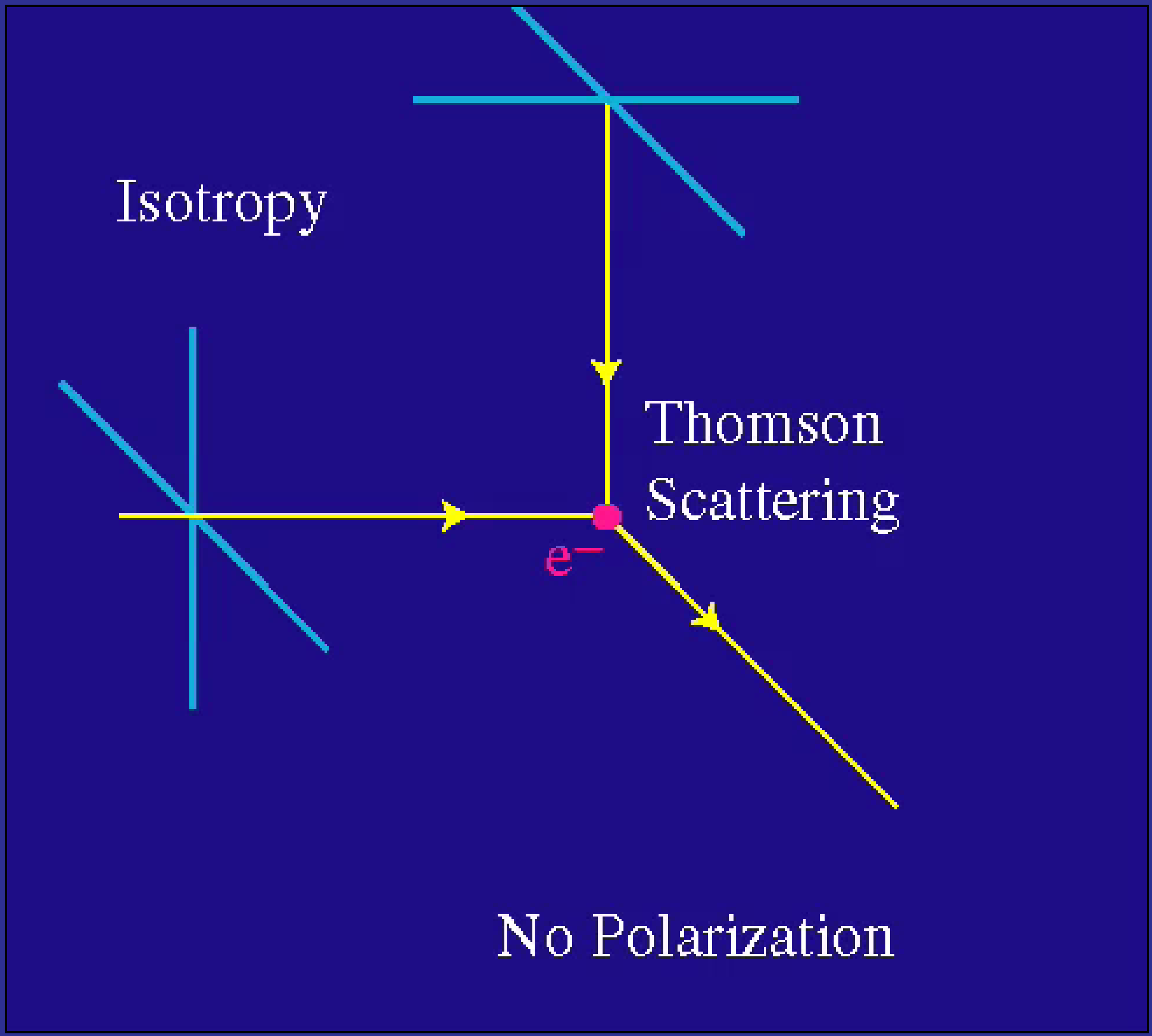
Polarization

- Like light scattering off surface, scattering with electrons polarizes radiation



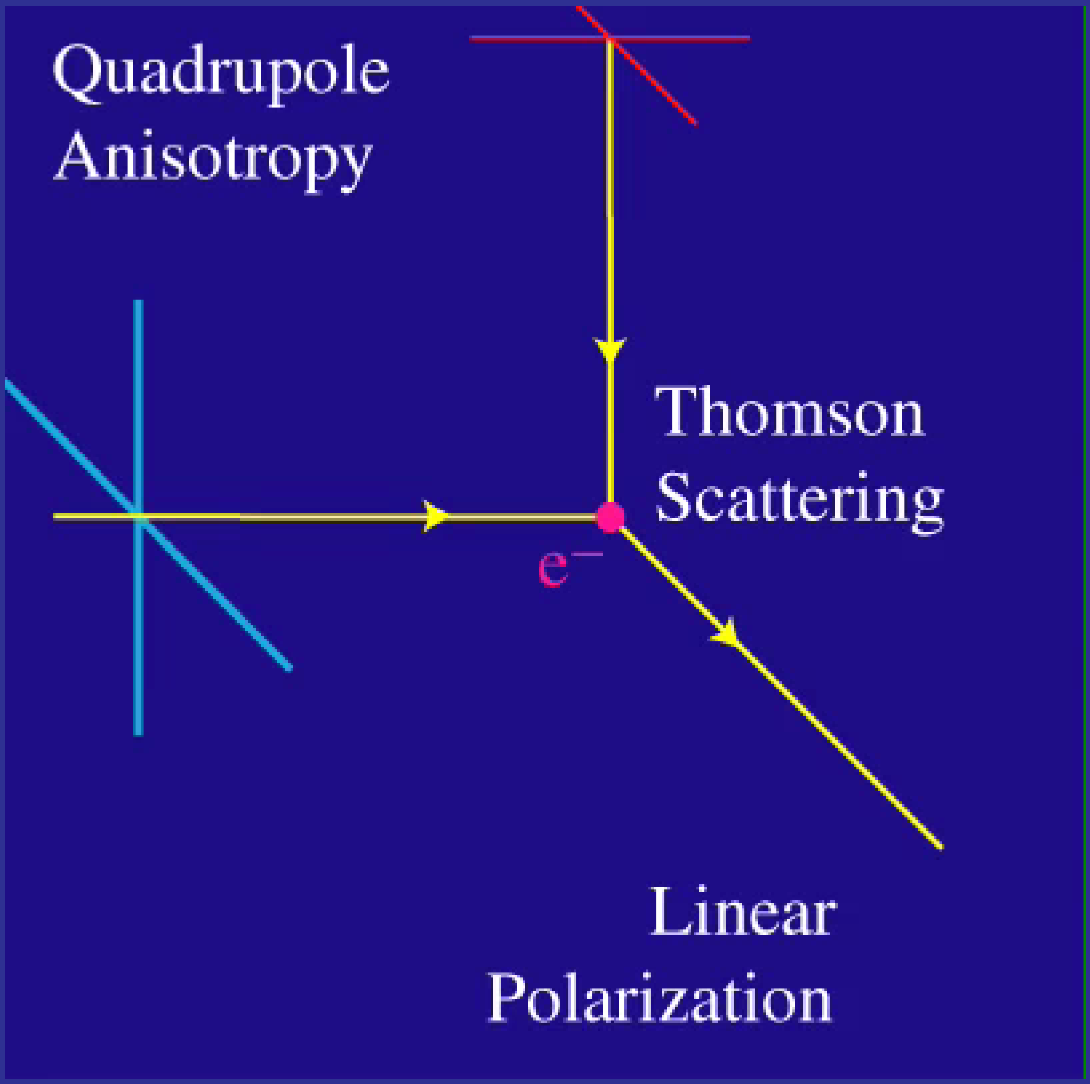
Polarization

- Unlike sunlight, CMB radiation comes from and electrons respond in all directions



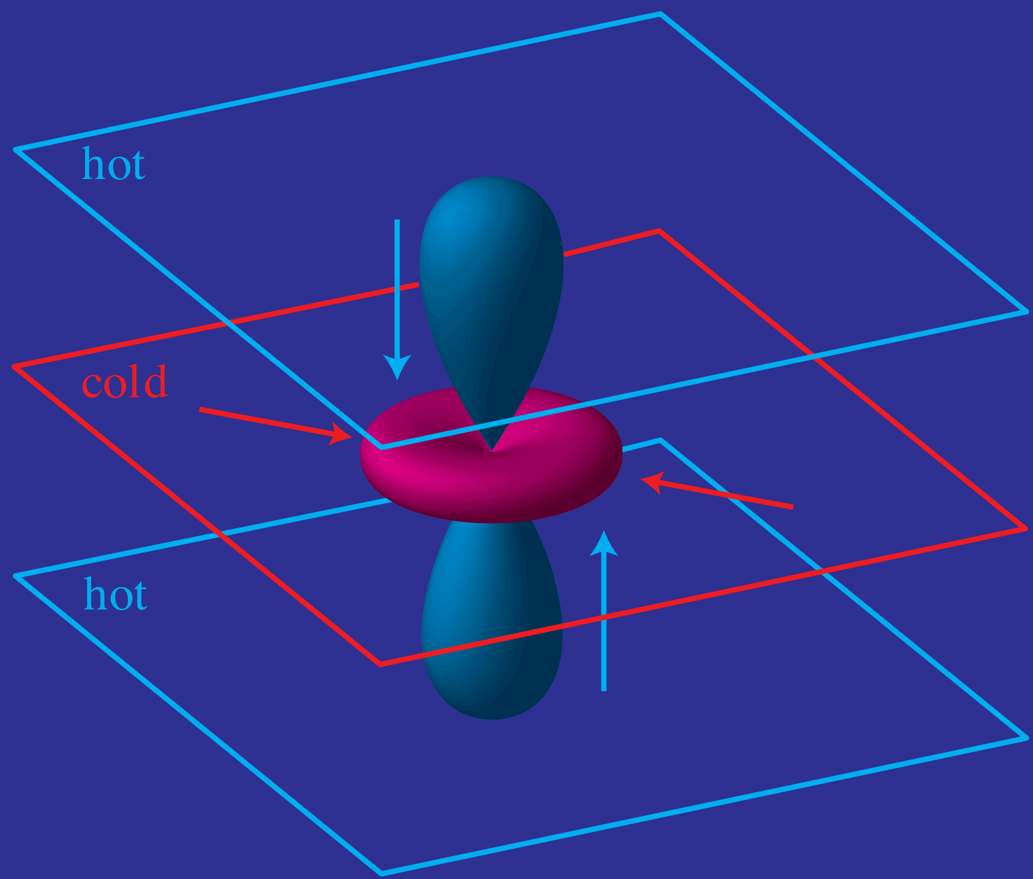
Polarization

- If intensity differs at 90 degrees (quadrupole anisotropy), net linear polarization



Whence Quadrupoles?

- Temperature inhomogeneities in a medium
- Photons arrive from different regions producing an anisotropy

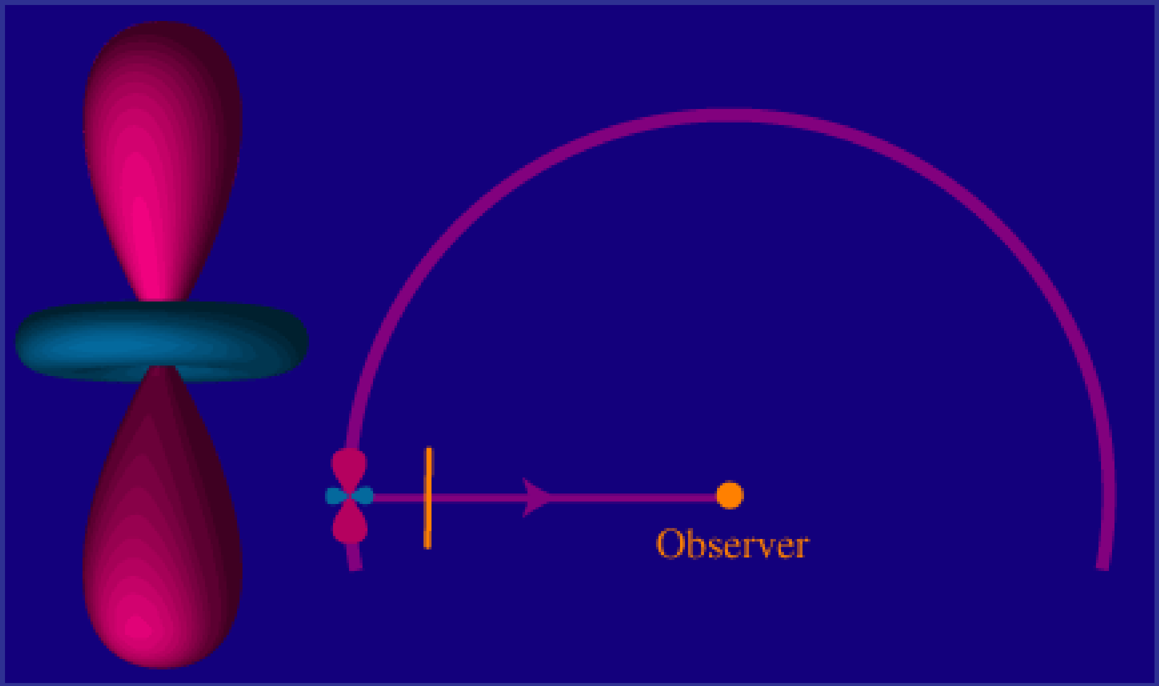


(Scalar) Temperature Inhomogeneity

Hu & White (1997)

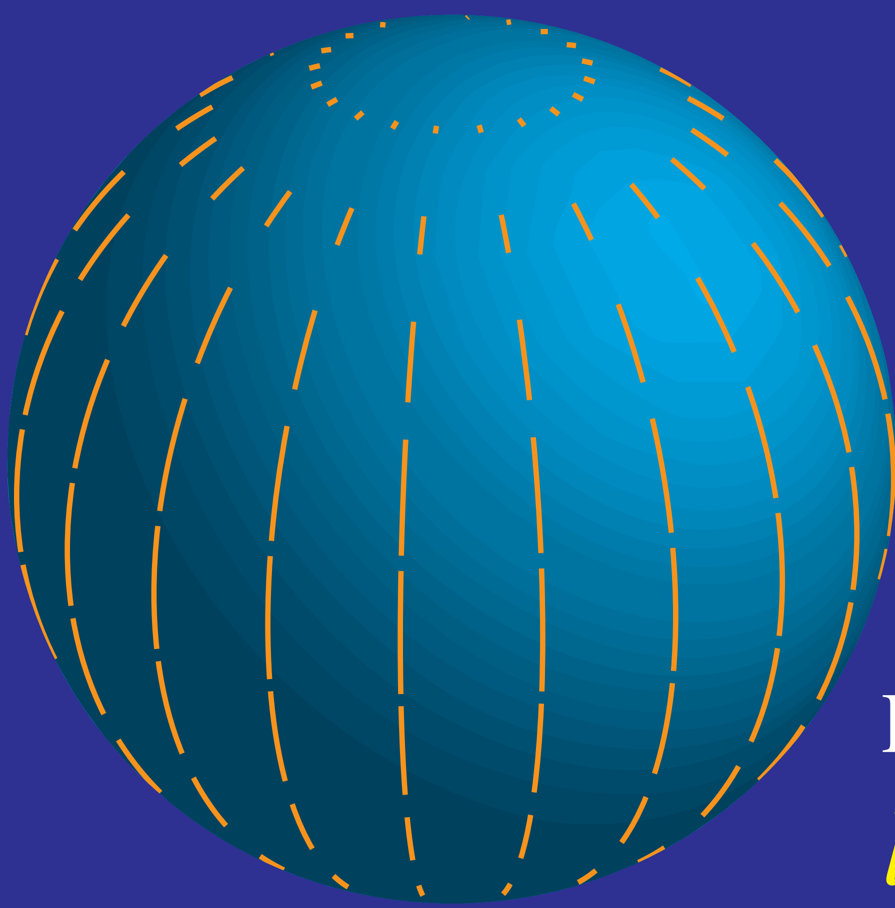
Patterns on the Sky

- Projection of the quadrupole moment across sky determines polarization pattern



E-mode Polarization

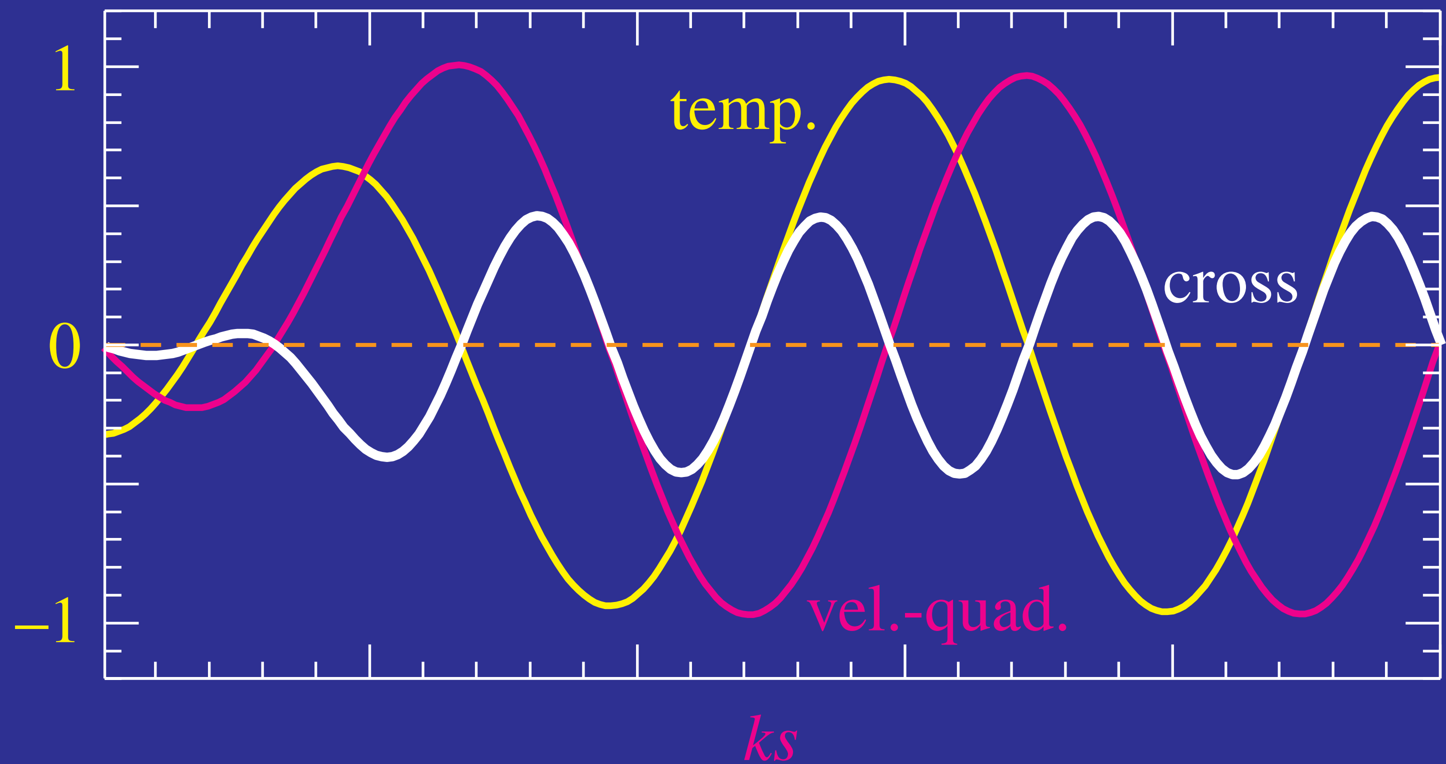
- Polarization points along the direction of plane wave or amplitude variation



E-tensor harmonic
$l=2,\ m=0$

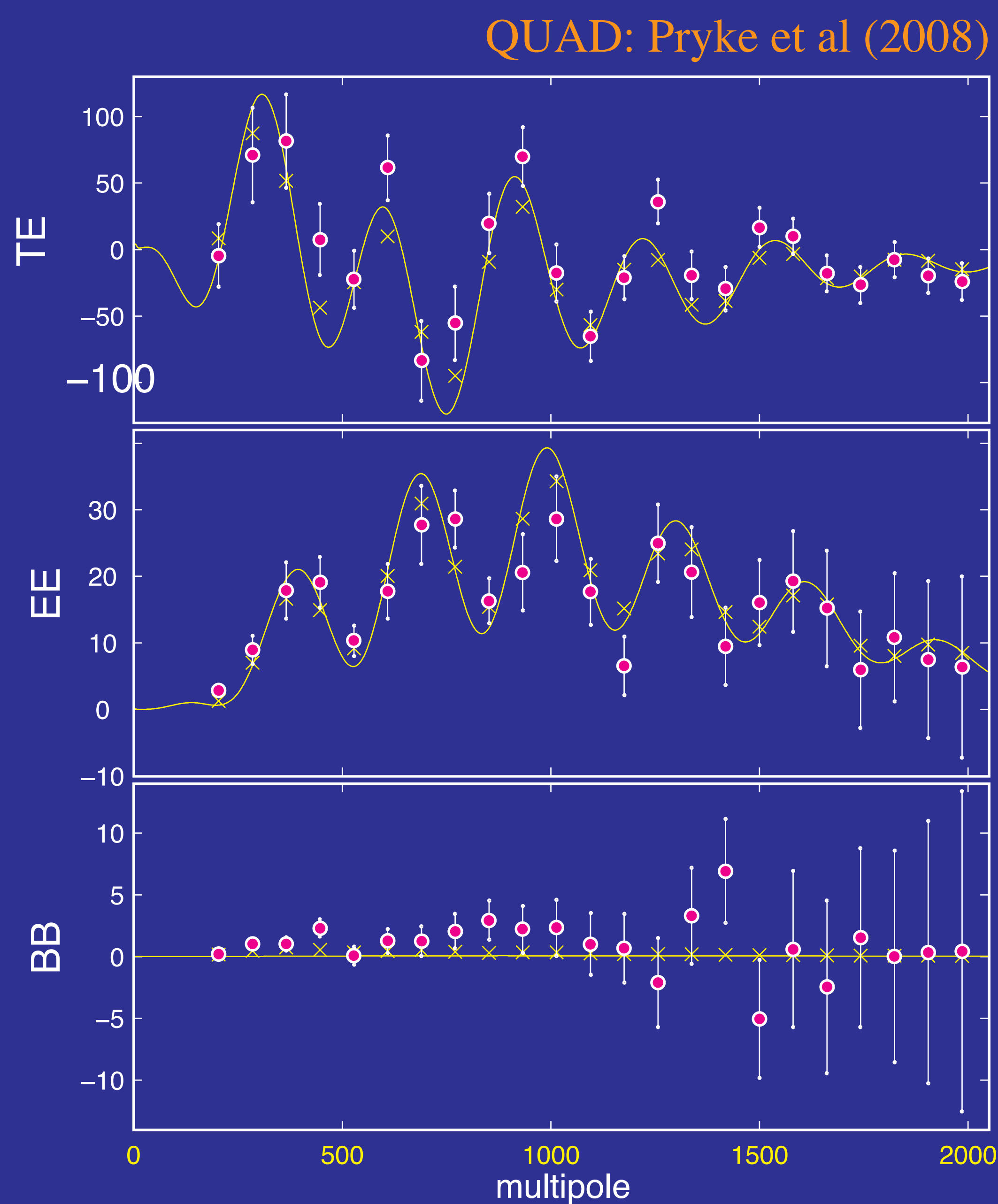
Acoustic Peaks in the Polarization

- Scalar quadrupole follows the velocity perturbation
- Acoustic velocity out of phase with acoustic temperature
- Correlation oscillates at twice the frequency

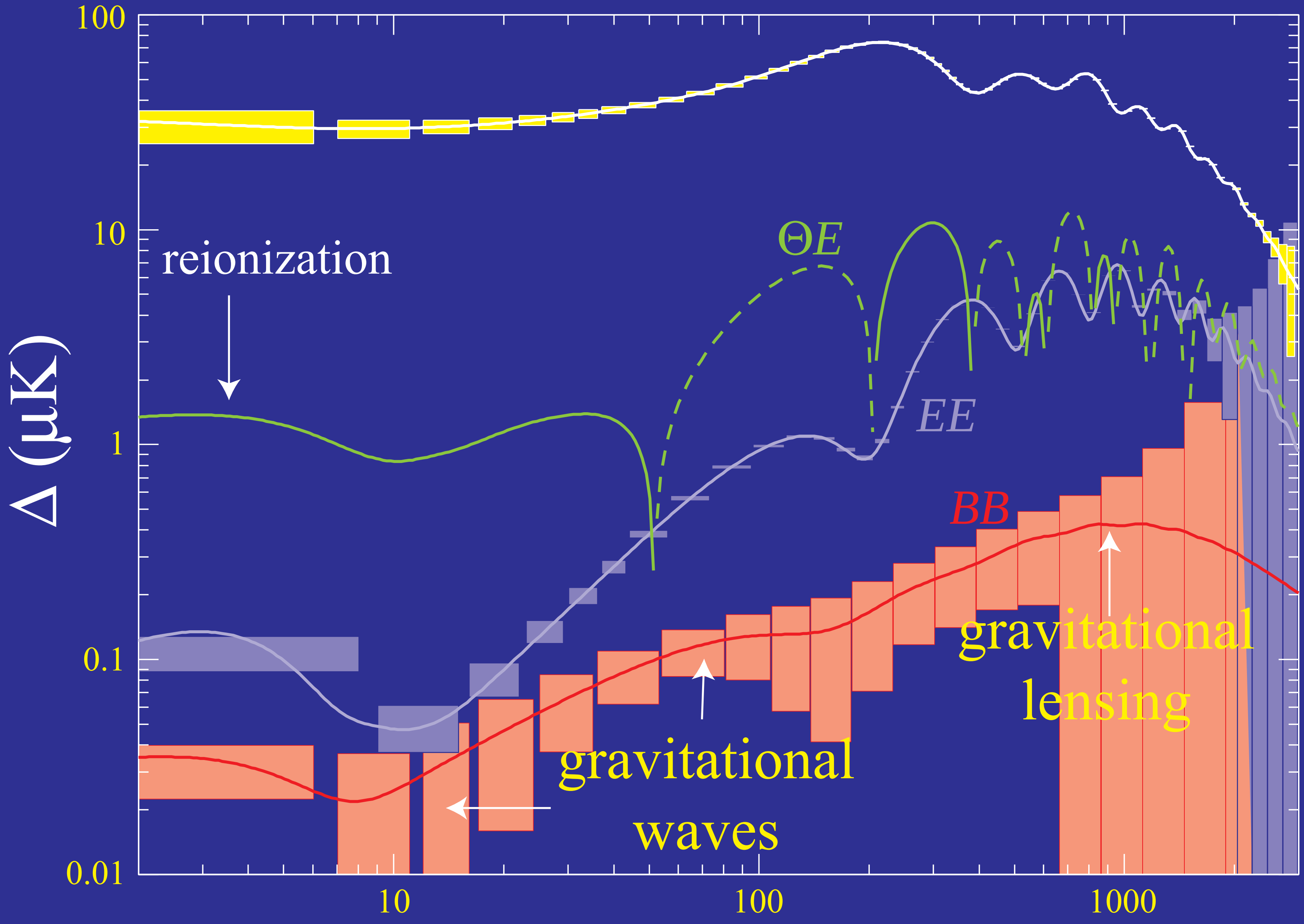


Hu & White (1997)

Power Spectrum Present



Polarized Landscape

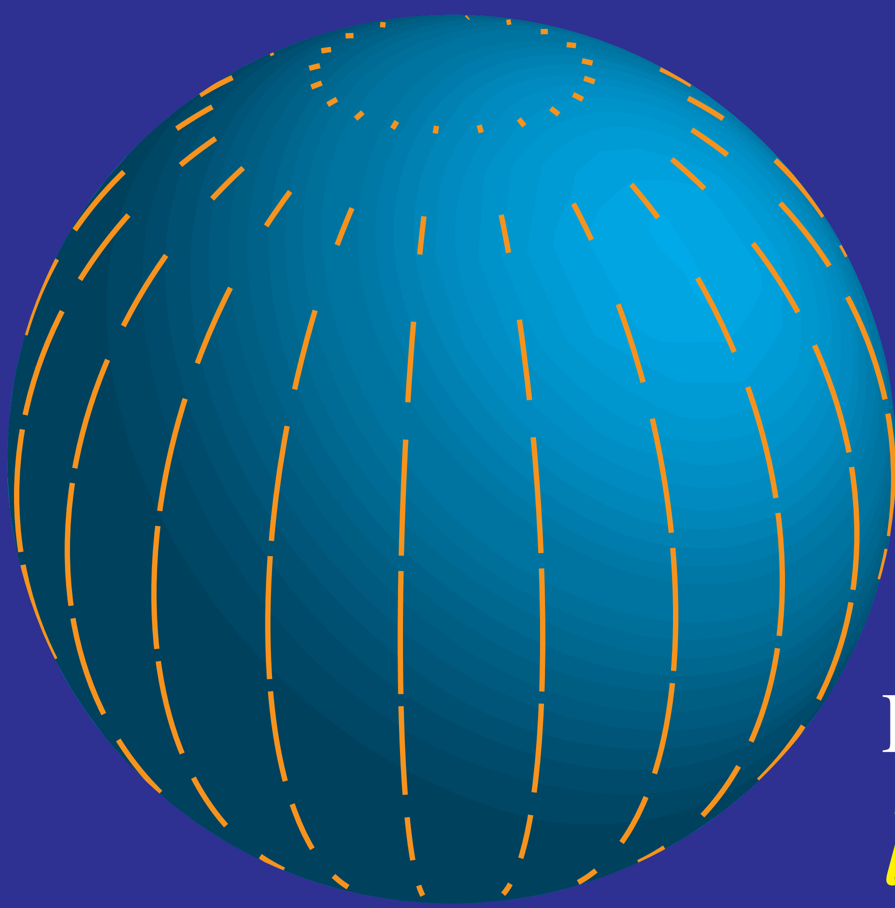


Hu & Dodelson (2002)

B-mode Polarization

E-mode Polarization

- Polarization points along the direction of plane wave or amplitude variation



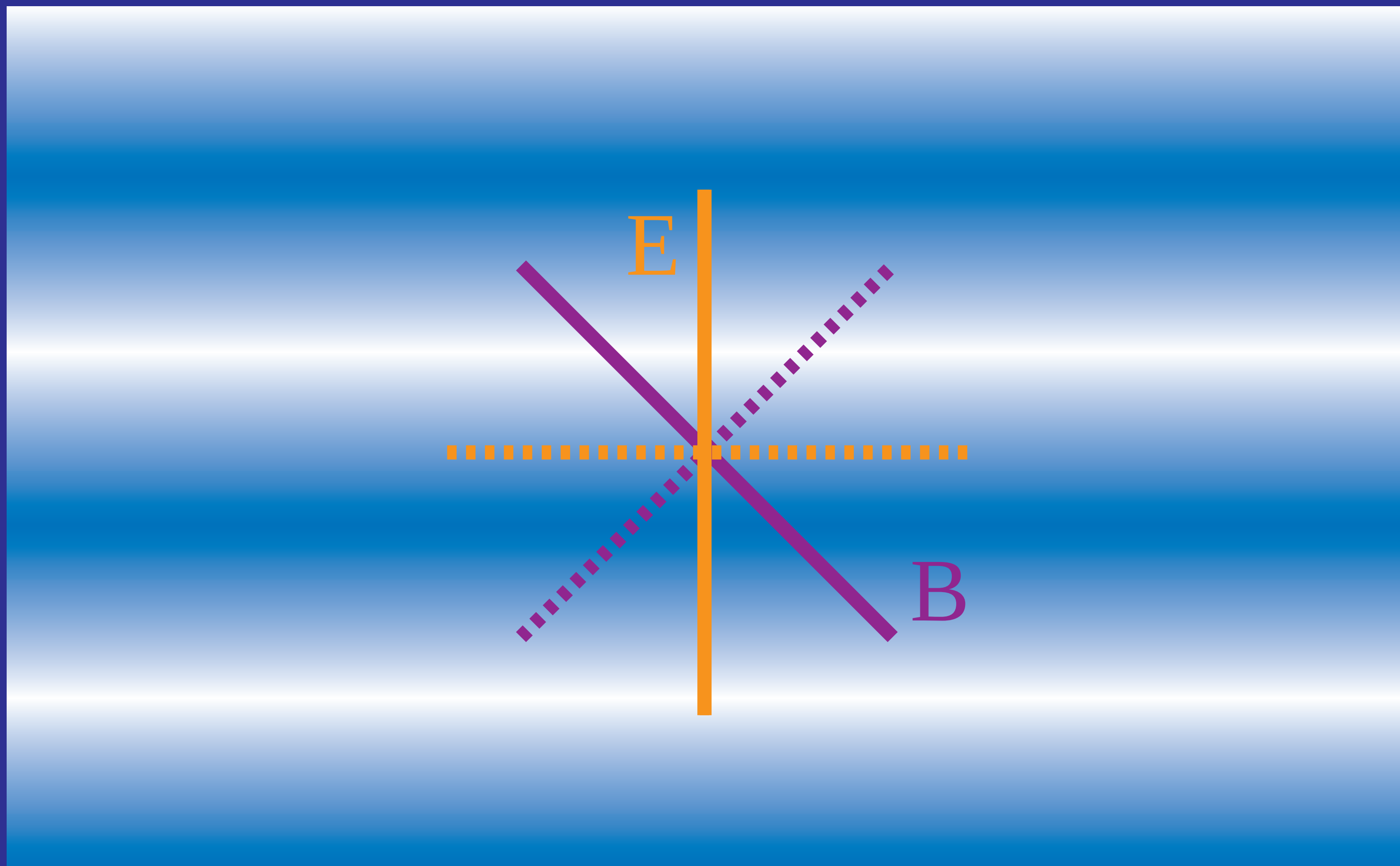
E-tensor harmonic

$l=2, m=0$

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)

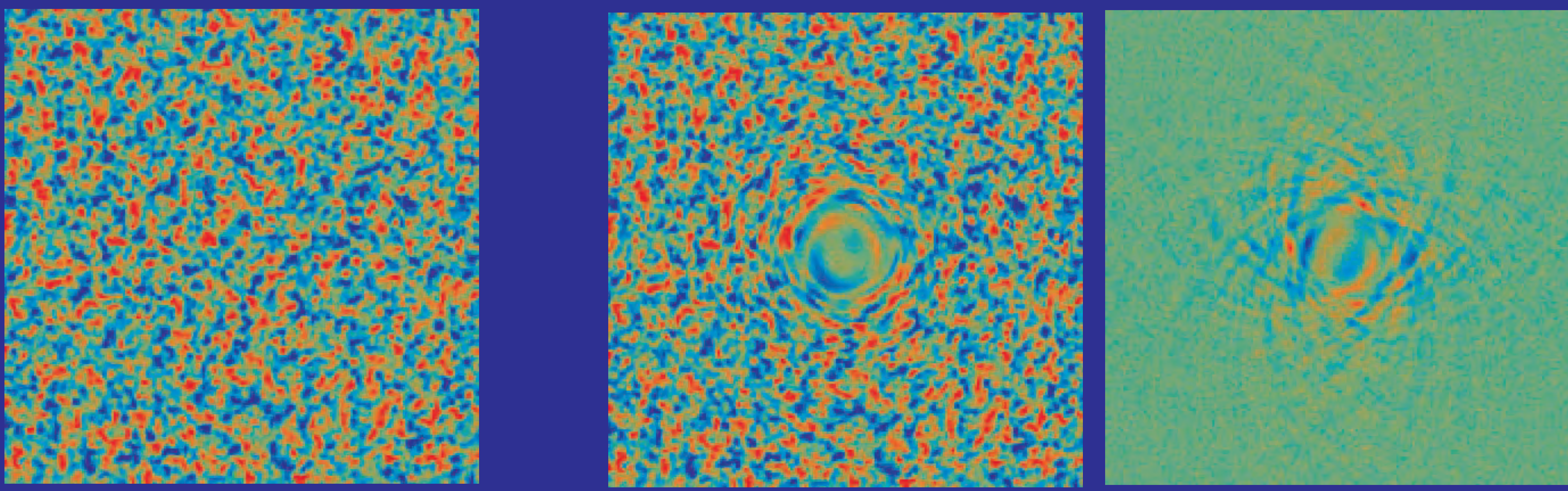
Gravitational Lensing

Example of CMB Lensing

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

Polarization Lensing

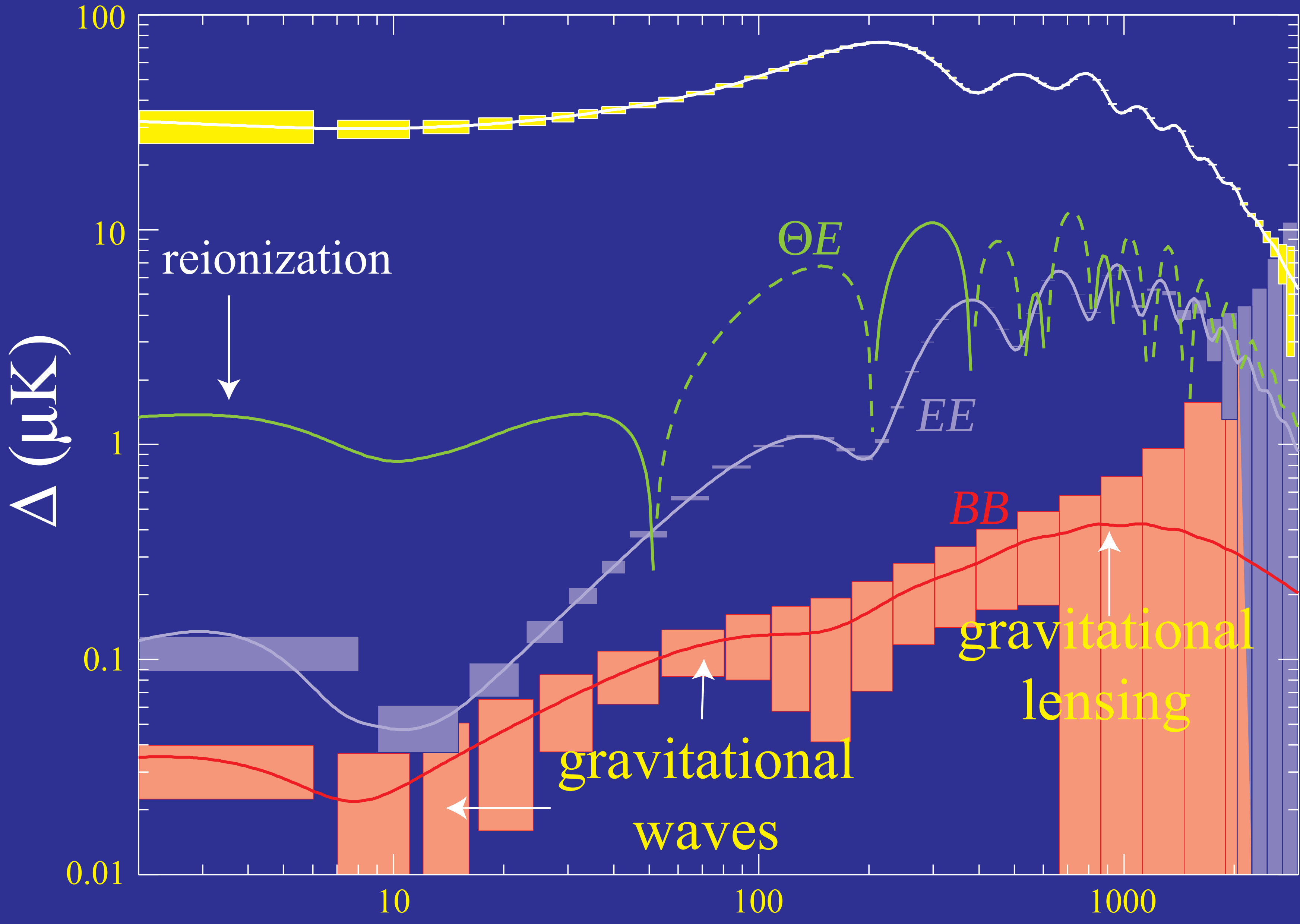
- Since E and B denote the relationship between the polarization amplitude and direction, warping due to lensing creates B-modes



Original Lensed E Lensed B

Zaldarriaga & Seljak (1998) [figure: Hu & Okamoto (2001)]

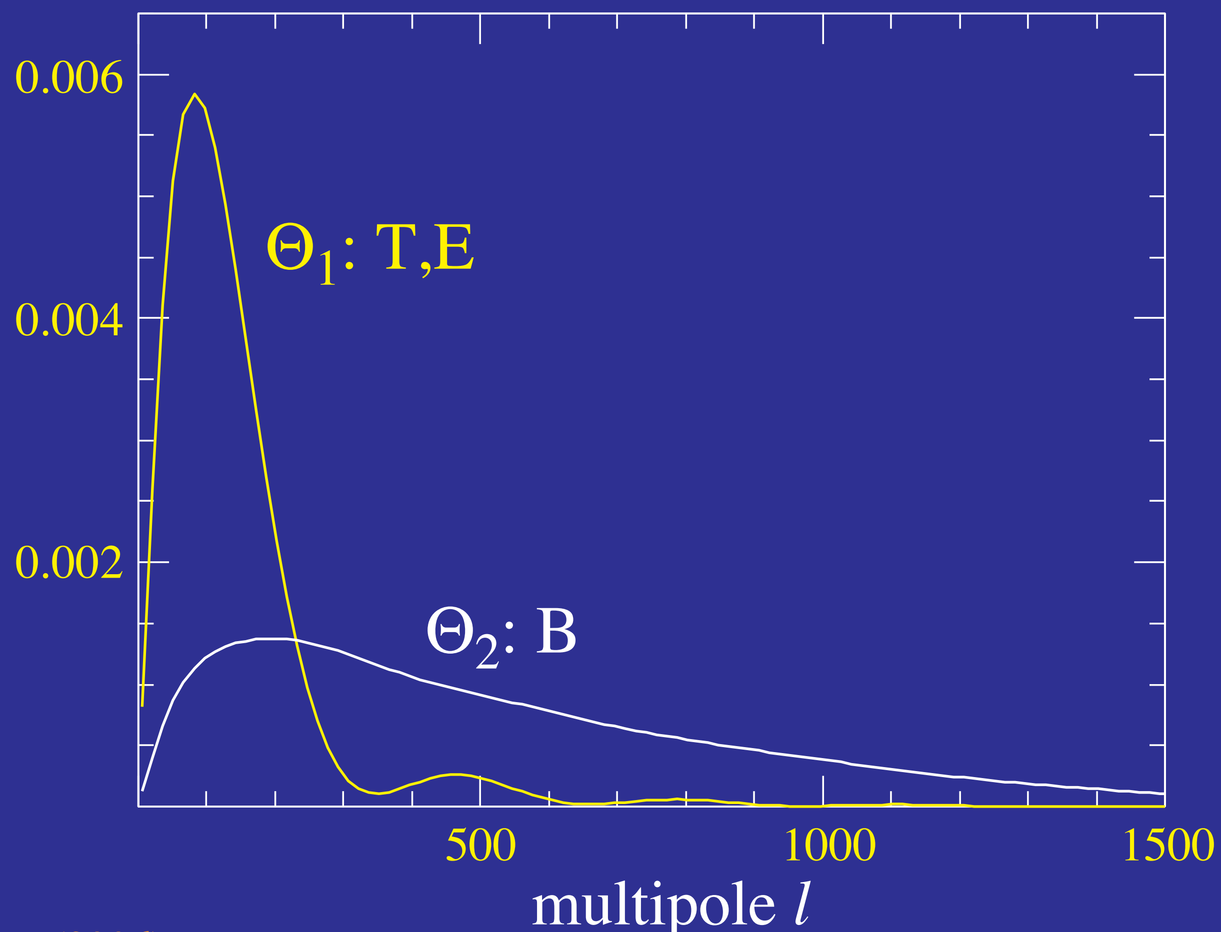
Polarized Landscape



Hu & Dodelson (2002)

Lensed Power Spectrum Observables

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

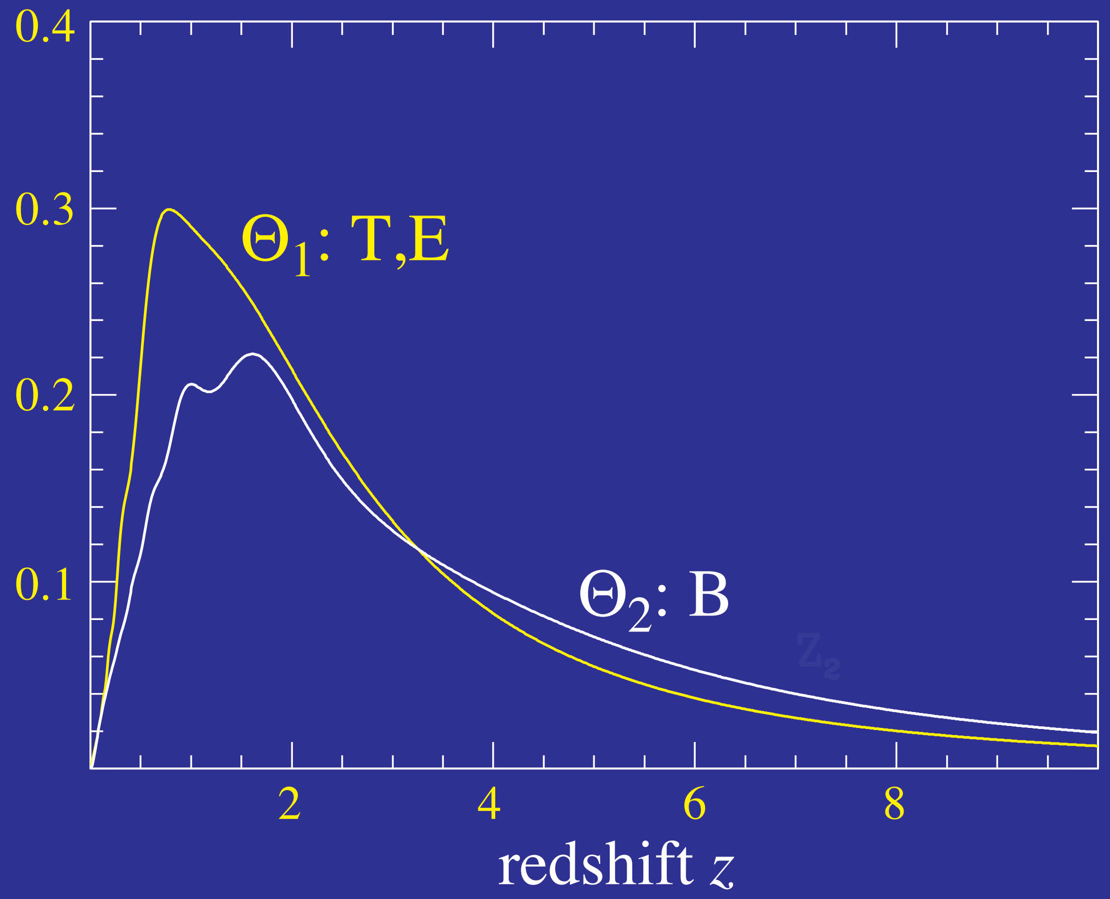


Smith, Hu & Kaplinghat (2006)

Redshift Sensitivity

- Lensing observables probe distance and structure at high redshift

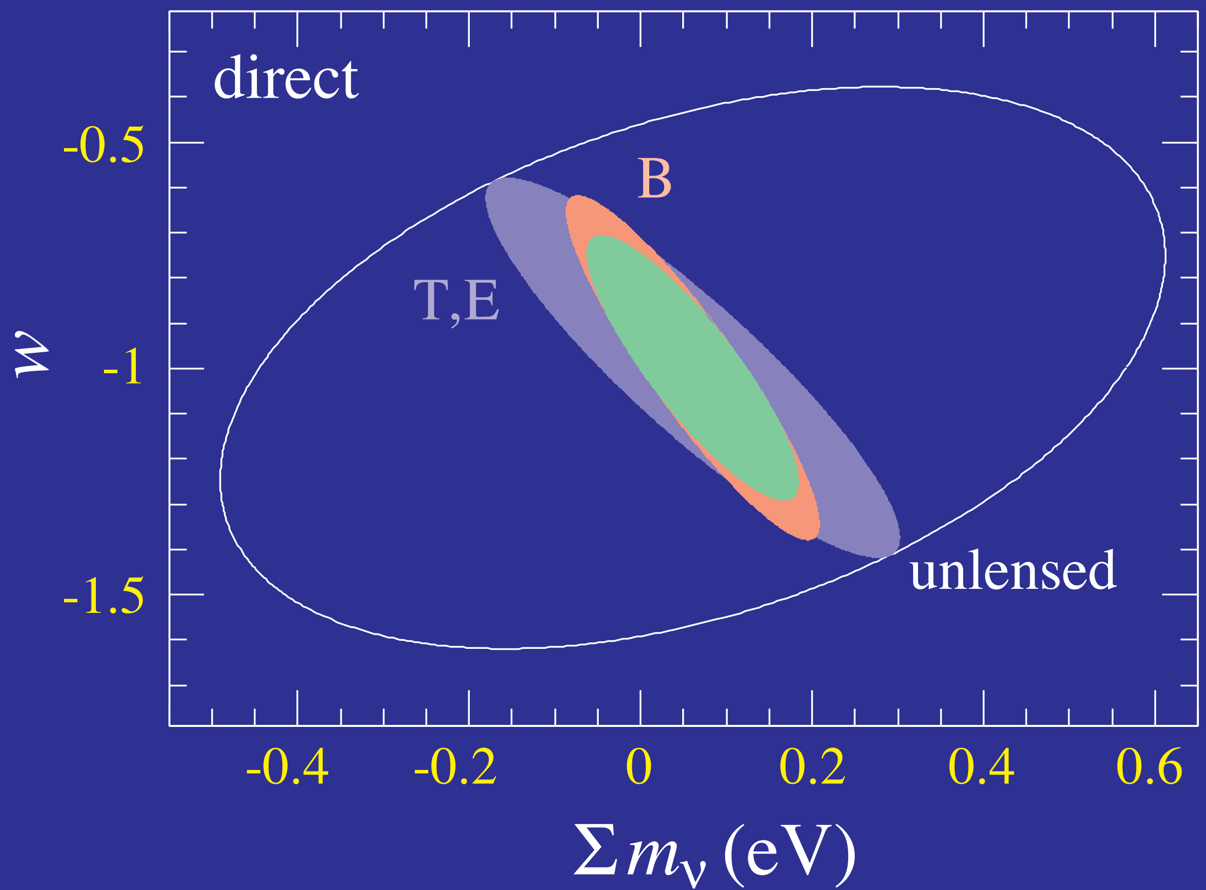
$$\frac{\delta\Theta_i}{\Theta_i} = \left[\left(3 - \frac{d\ln\Delta_m^2}{d\ln k}\right)\frac{\delta D_A}{D_A} - \frac{\delta H}{H} + 2\frac{\delta G}{G} + 2\frac{\delta D_A(D_s - D)}{D_A(D_s - D)} \right]$$



Smith, Hu & Kaplinghat (2006)

Lensing Observables

- Lensing observables provide a simple way of accounting for non-Gaussianity and parameter degeneracies
- Direct forecasts for Planck + 10% sky with noise Δ_P=1.4uK'



Smith, Hu, Kaplinghat (2006) [see also: Kaplinghat et. al 2003, Acquaviva & Baccigalupi 2005, Smith et al 2005, Li et al 2006]

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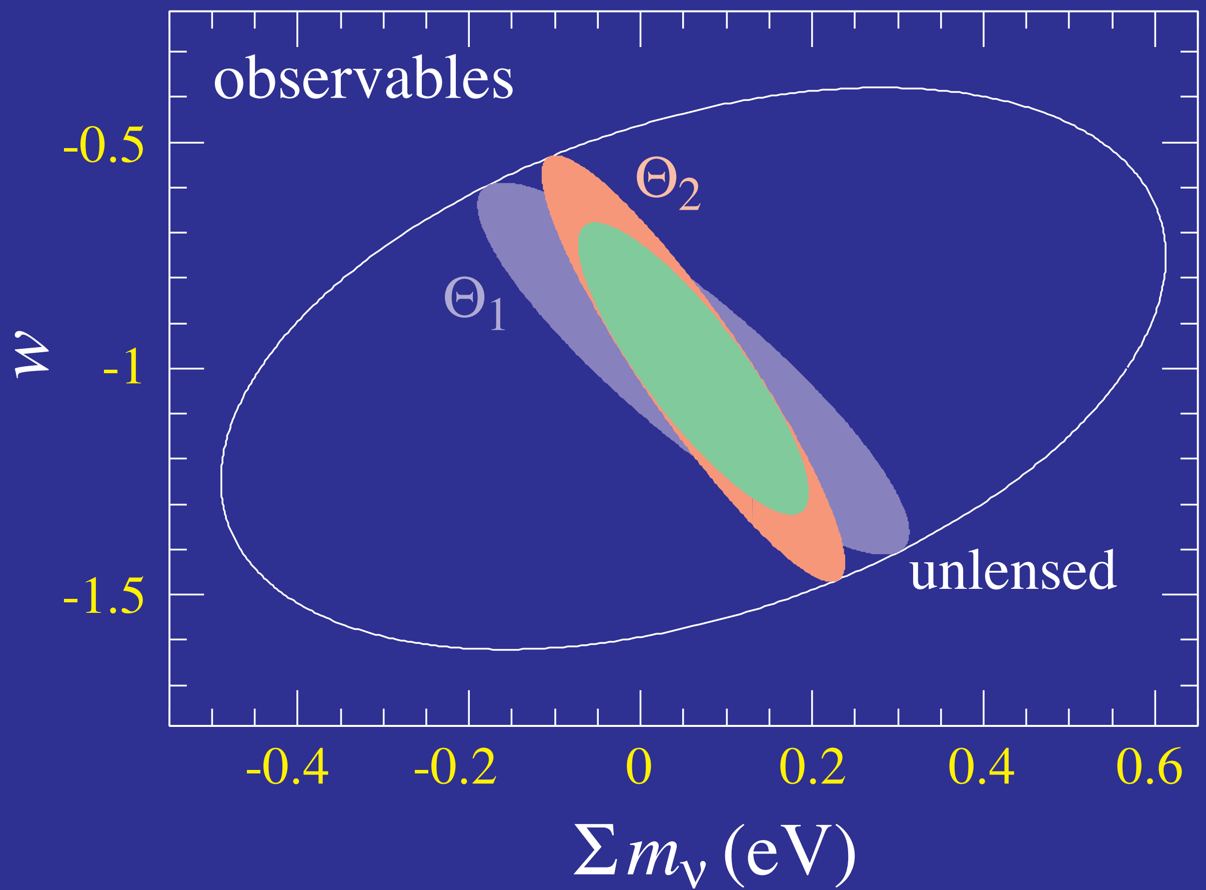
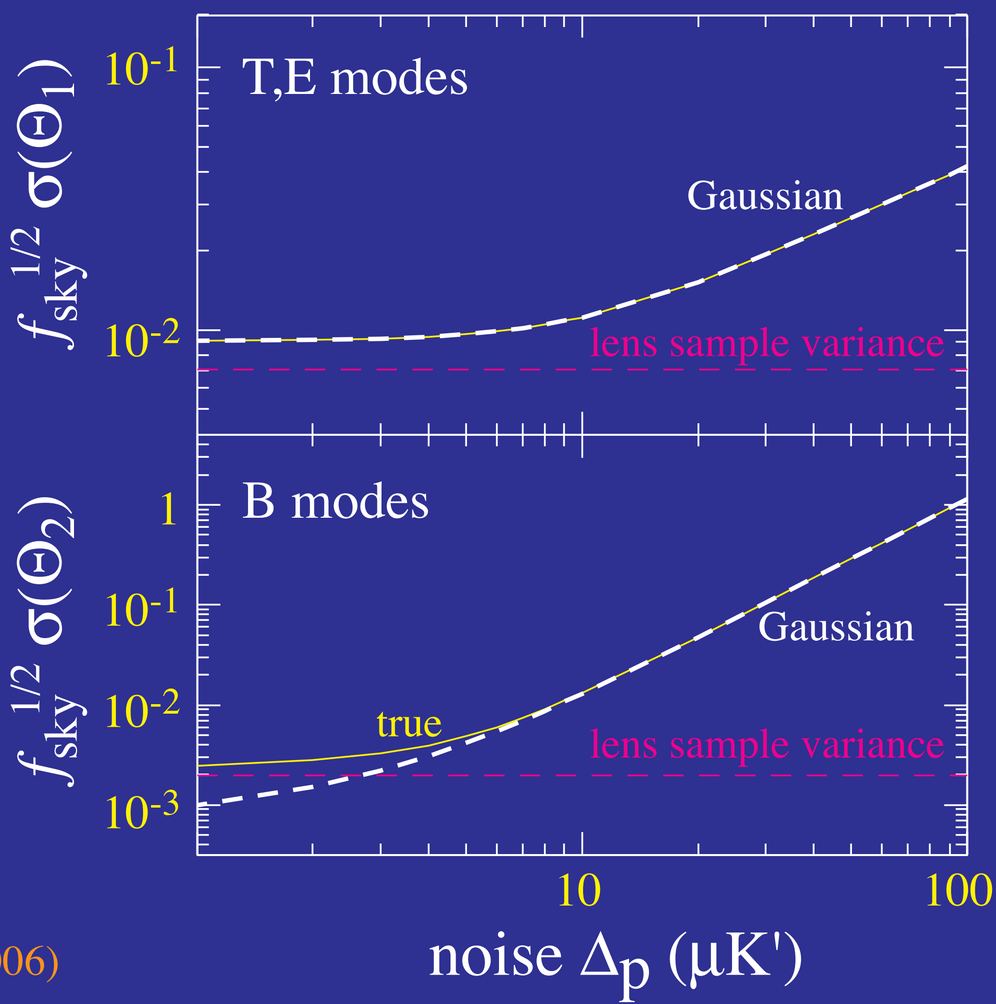


Smith, Hu, Kaplinghat (2006)

Constraints on Lensing Observables

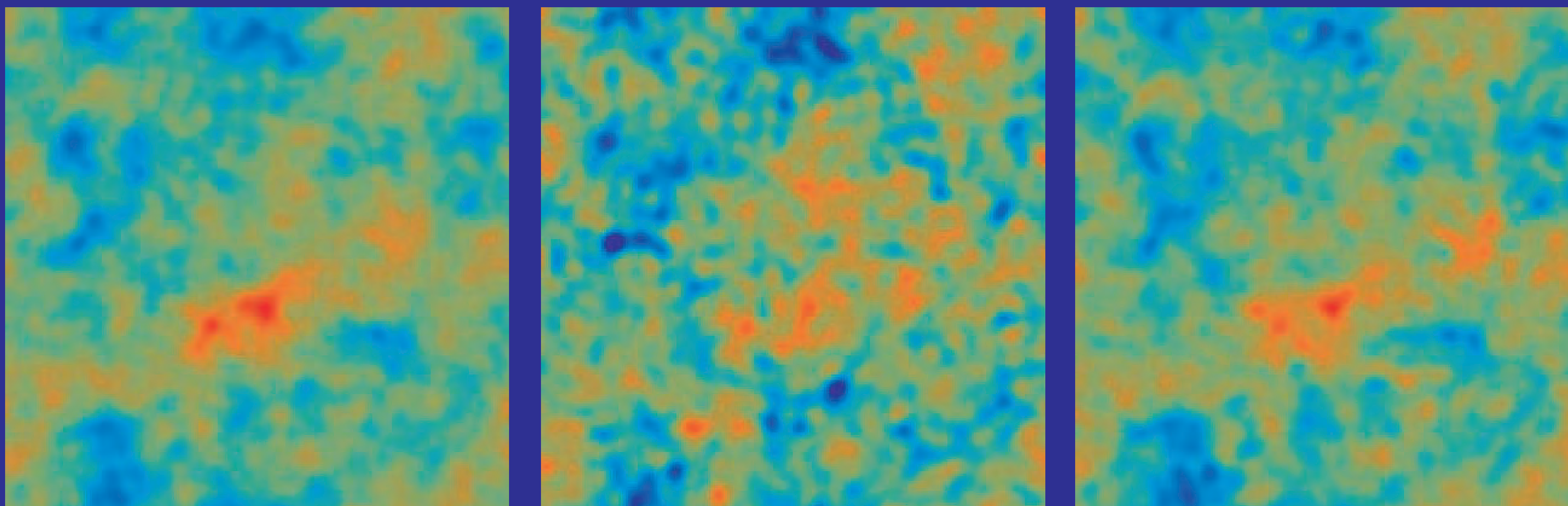
- Lensing observables in T,E are limited by CMB sample variance
- Lensing observables in B are limited by lens sample variance
- B-modes require 10x as much sky at high signal-to-noise or 3x as much sky at the optimal signal-to-noise with Δ_P=4.7uK'



Smith, Hu & Kaplinghat (2006)

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)



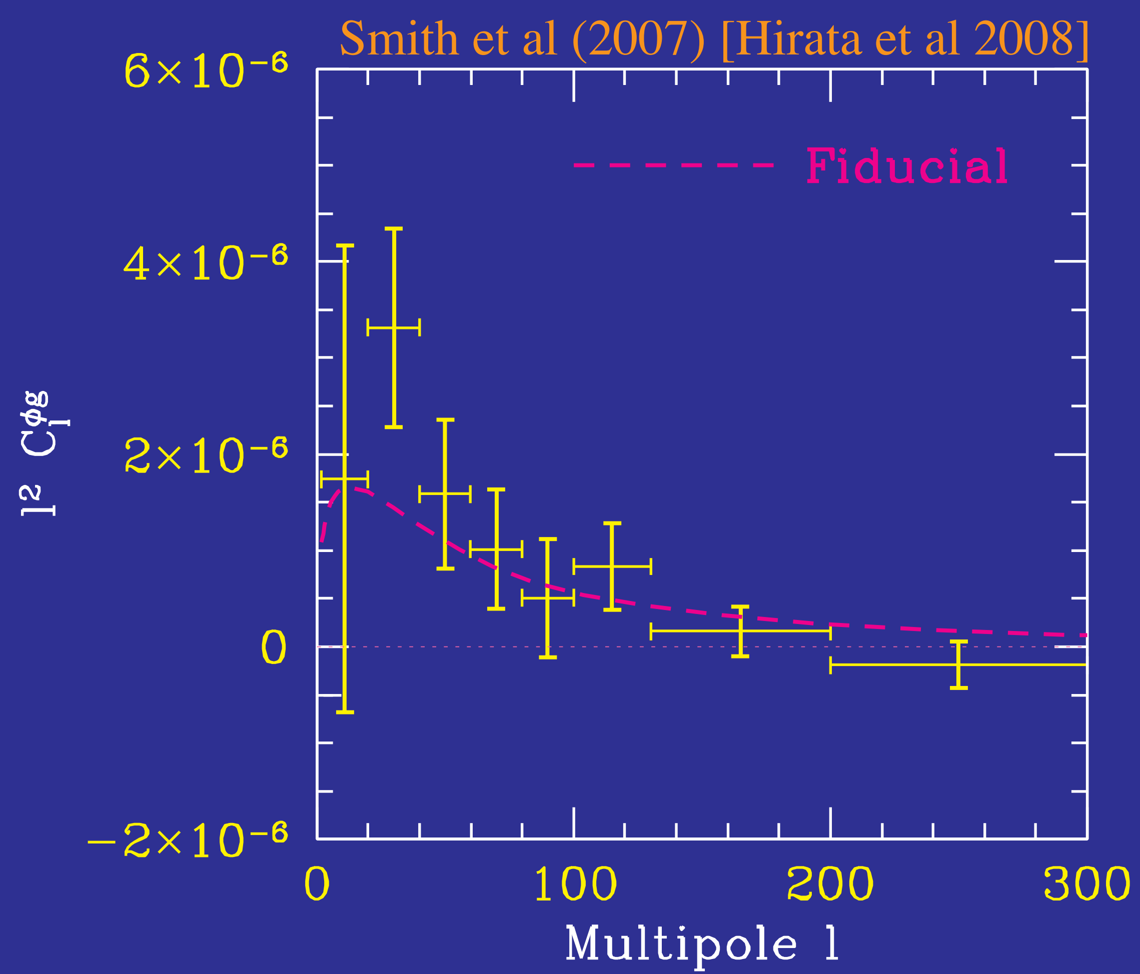
mass | temp. reconstruction | EB pol. reconstruction

100 sq. deg; 4' beam; 1μK-arcmin

Hu & Okamoto (2001)

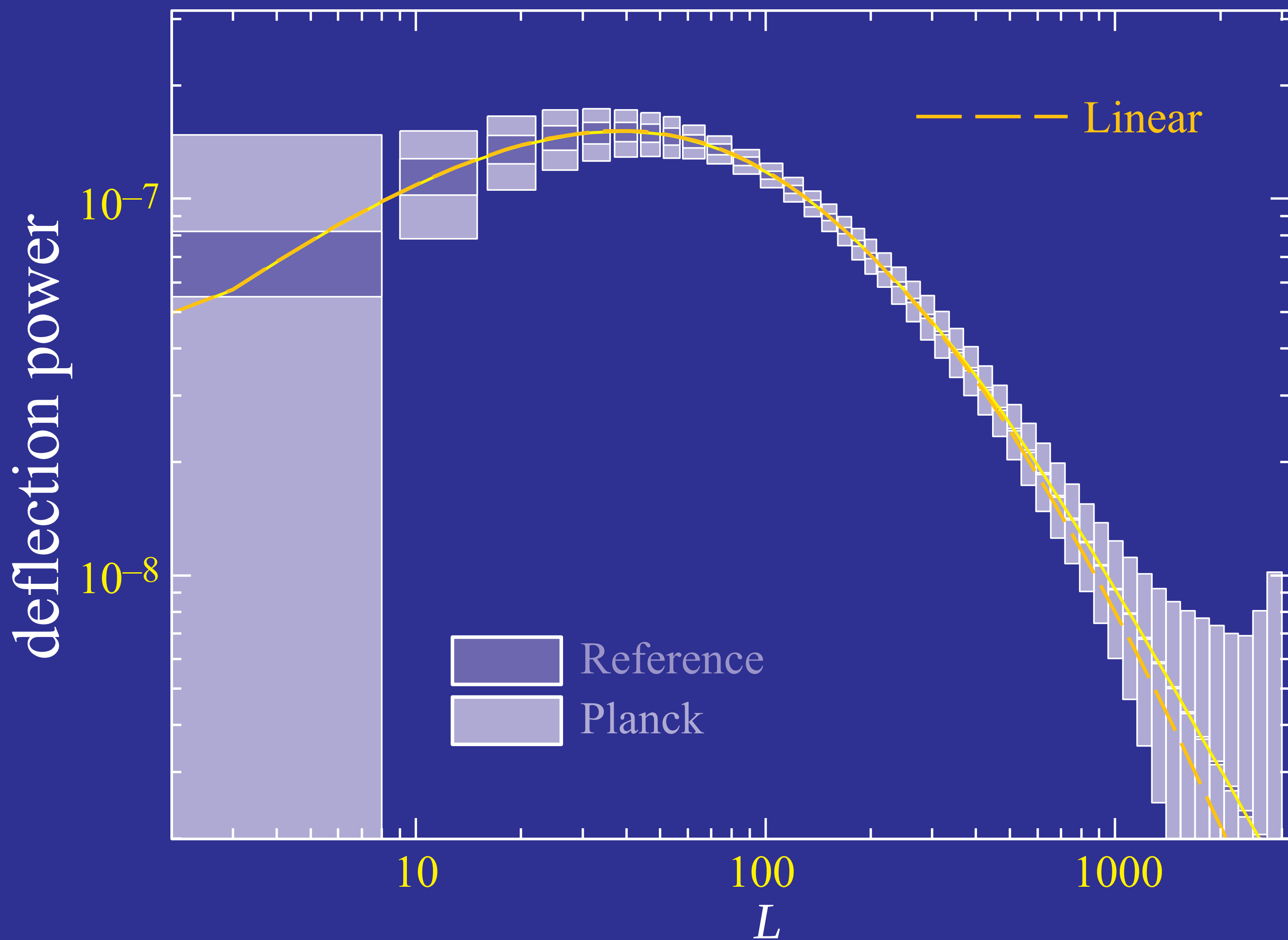
Lensing-Galaxy Correlation

- ~3σ+ joint detection of WMAP lensing reconstruction with large scale structure (galaxies)
- Consistent with ΛCDM



Matter Power Spectrum

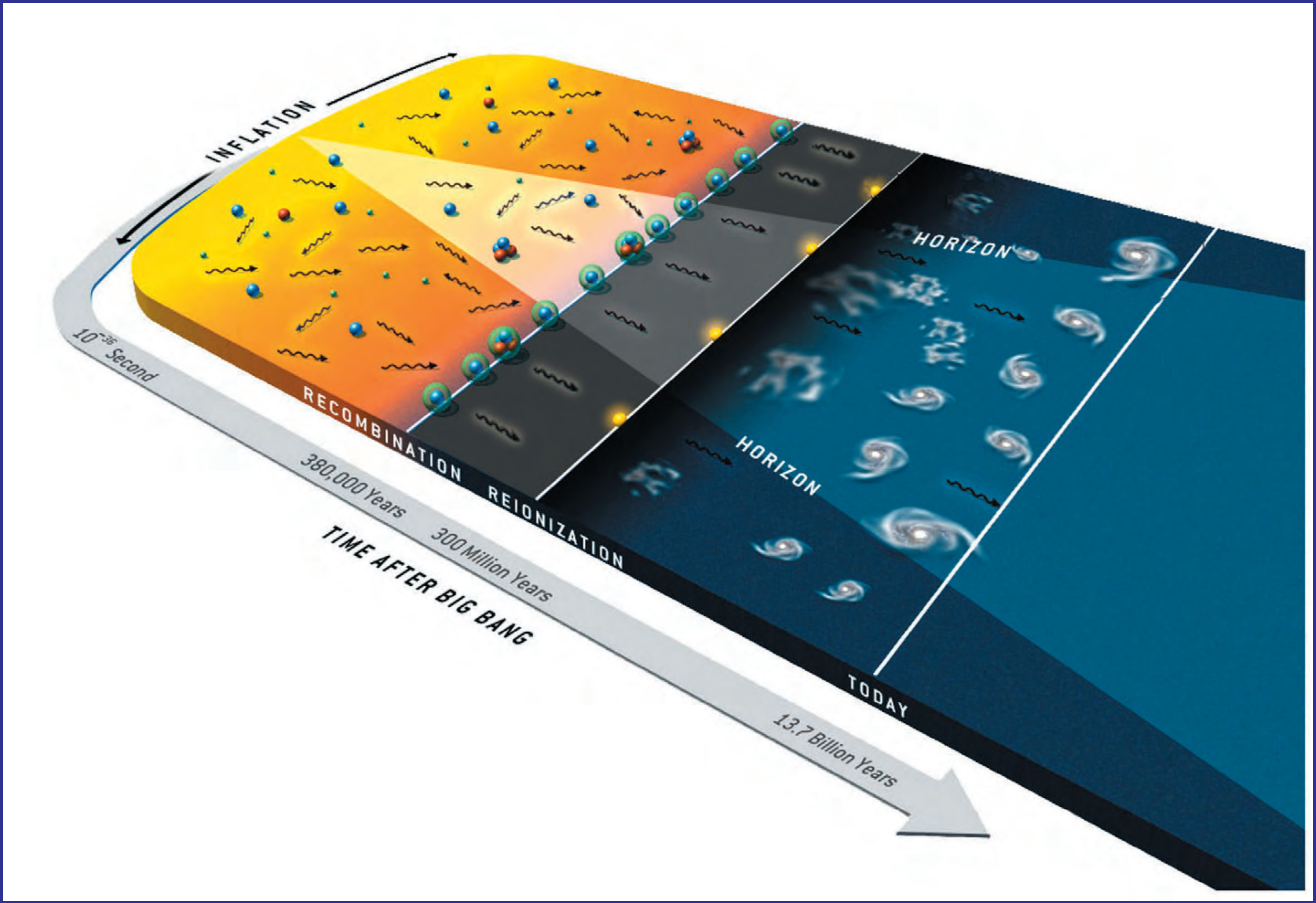
- Measuring projected matter power spectrum to cosmic variance limit across whole linear regime $0.002 < k < 0.2\ h$/Mpc



Hu & Okamoto (2001)

Reionization

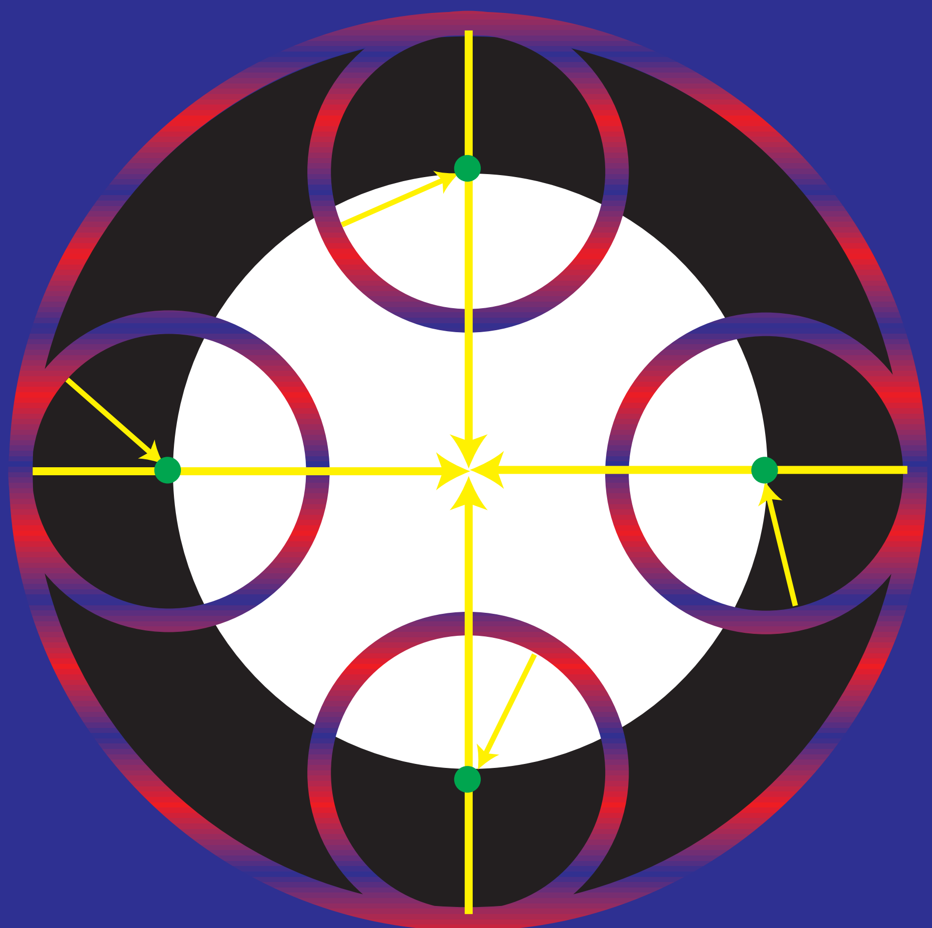
Across the Horizon



Hu & White (2004); artist:B. Christie/SciAm; available at http://background.uchicago.edu

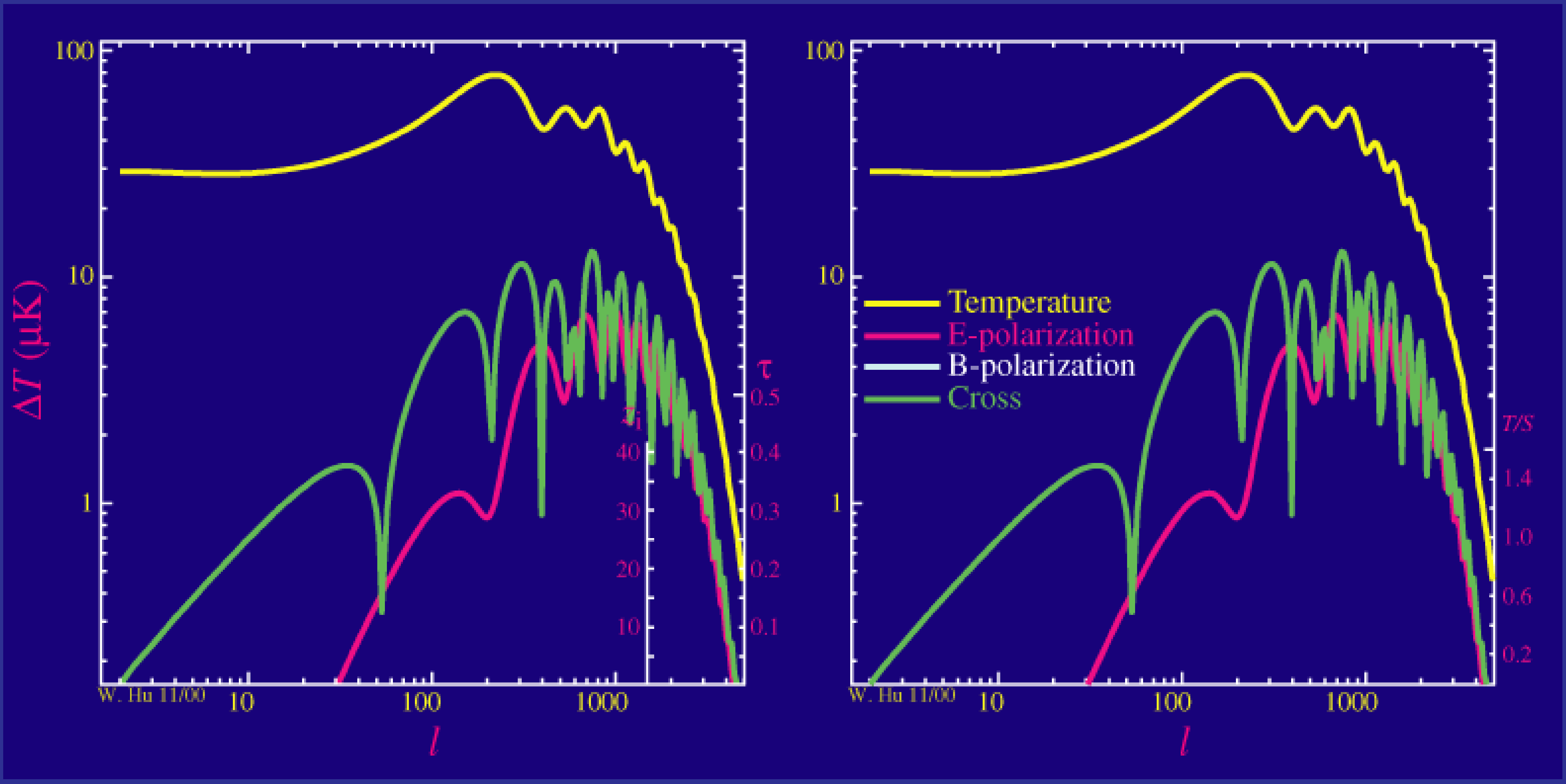
Anisotropy Suppression

- A fraction $\tau \sim 0.1$ of photons rescattered during reionization out of line of sight and replaced statistically by photon with random temperature flucutuation - suppressing anisotropy as $e^{-\tau}$



Reionization Suppression

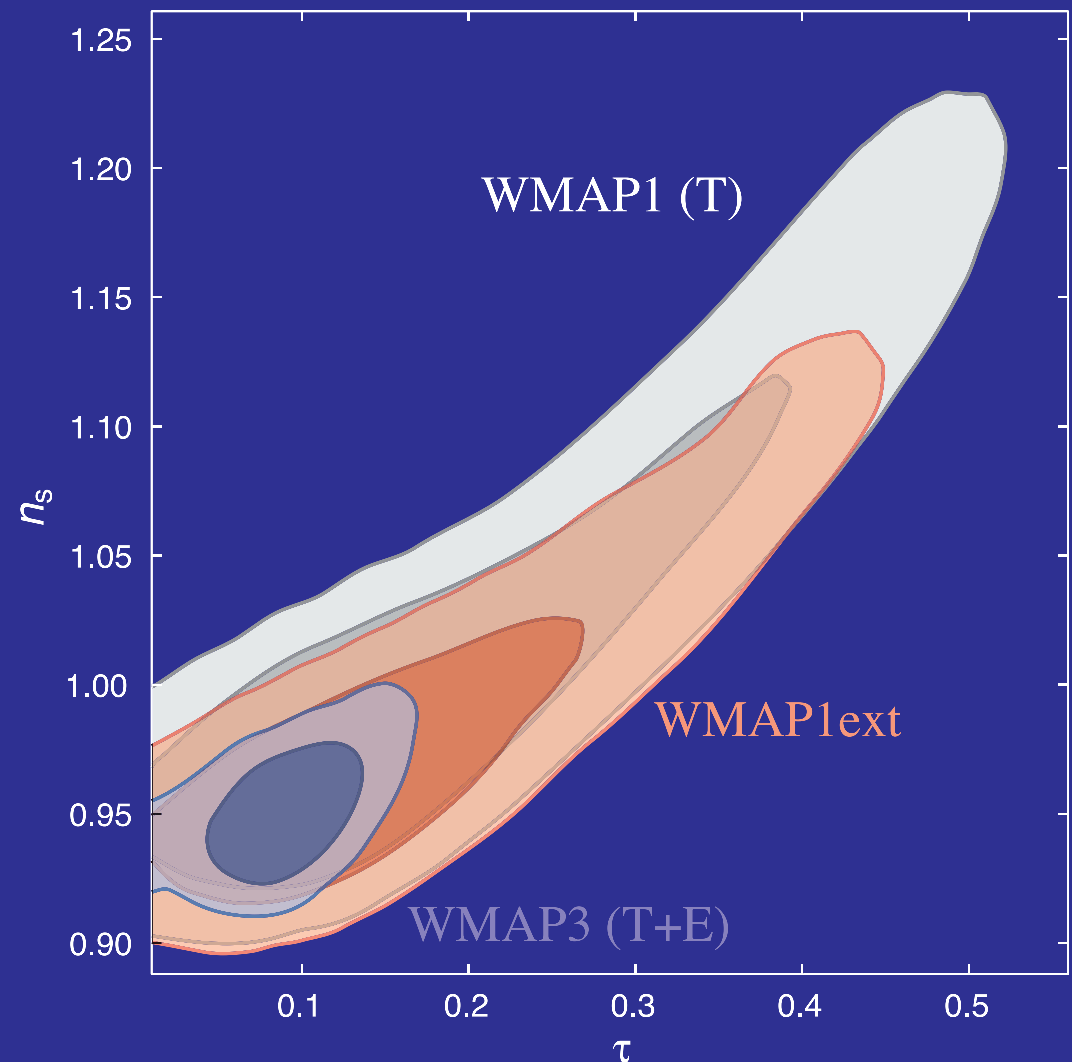
- Rescattering suppresses primary temperature and polarization anisotropy according to optical depth, fraction of photons rescattered



Tilt-τ Degeneracy

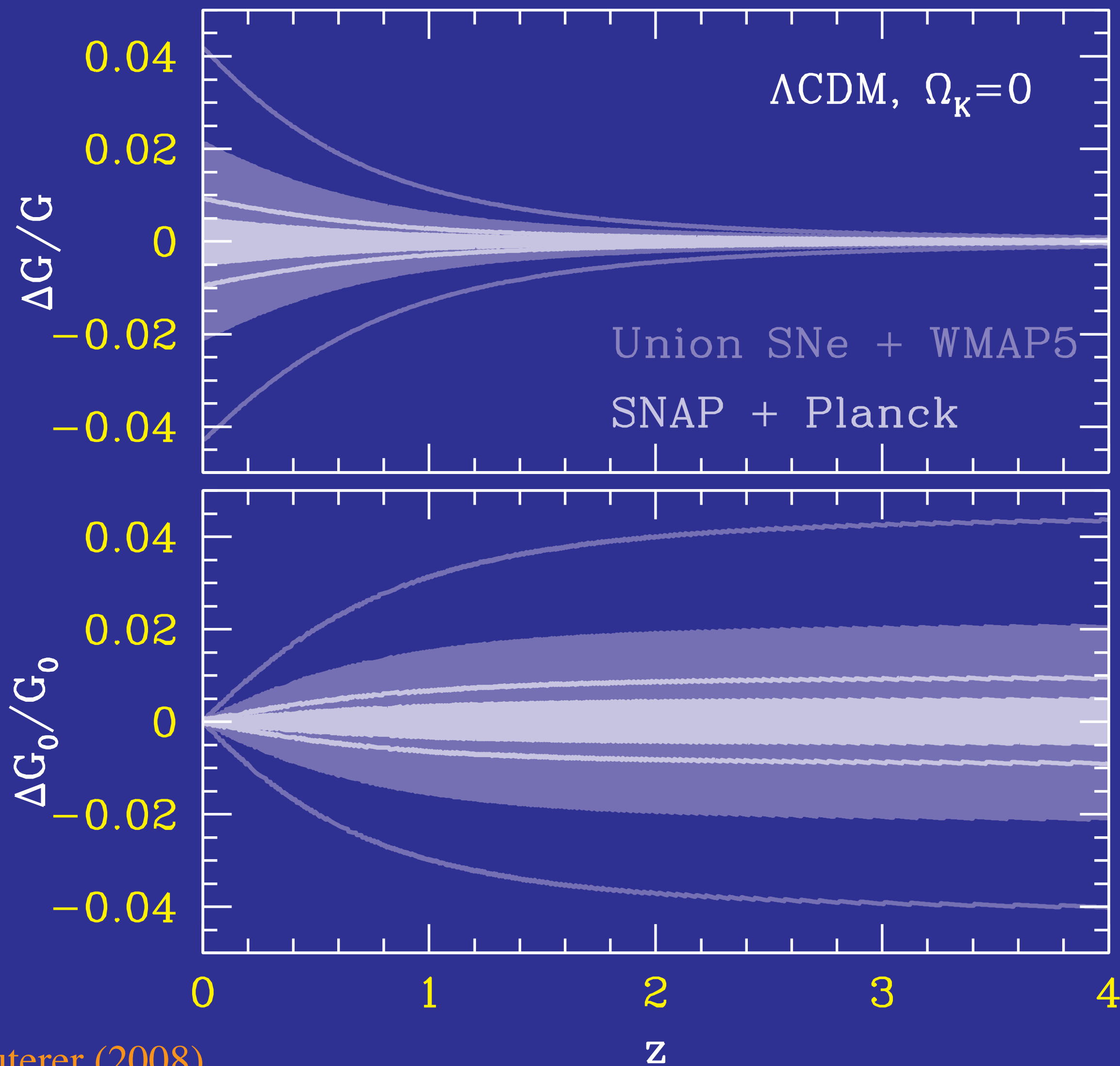
- Only anisotropy at reionization (high k), not isotropic temperature fluctuations (low k) - is suppressed leading to effective tilt for WMAP (not Planck)

Spergel et al (2006)



Distance Predicts Growth

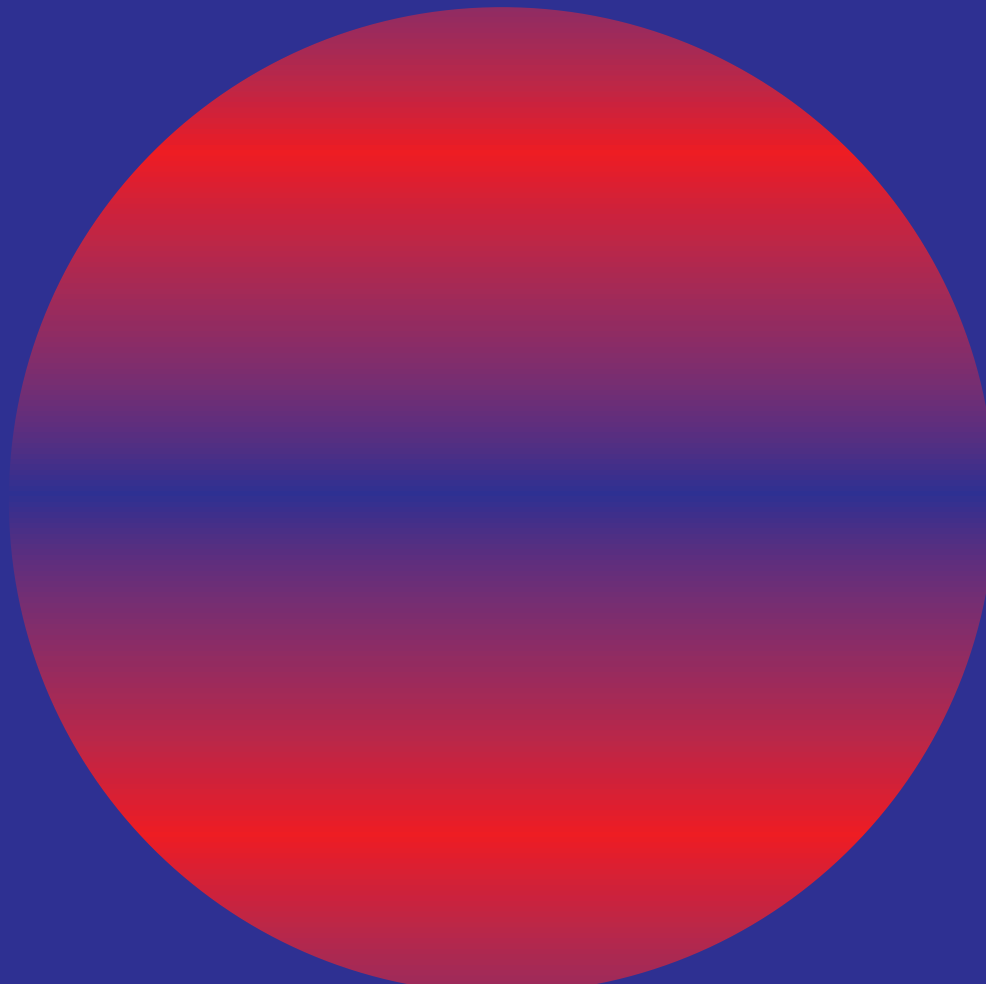
- With smooth dark energy, distance predicts scale-invariant growth to a few percent - a falsifiable prediction



Mortonson, Hu, Huterer (2008)

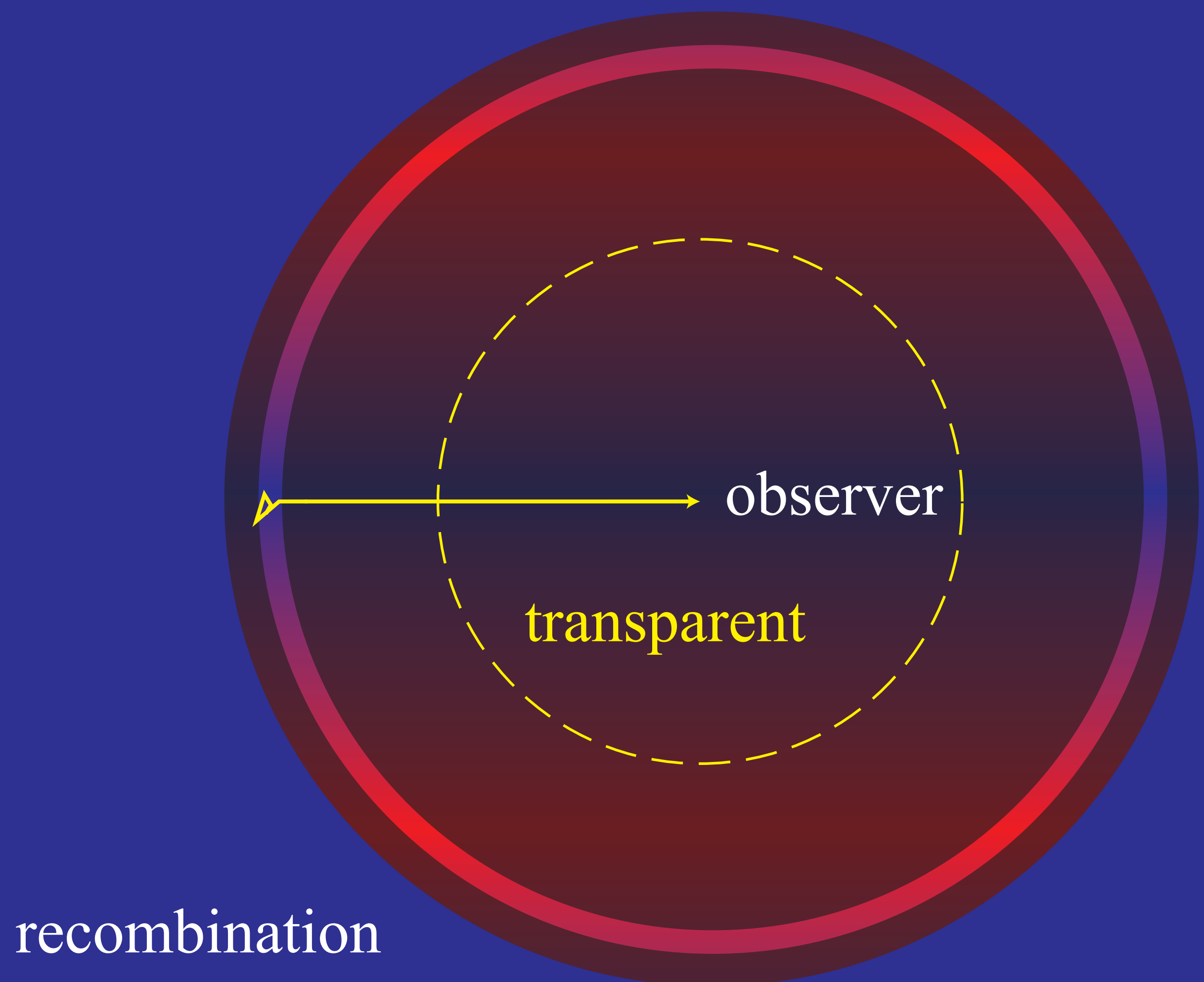
Temperature Inhomogeneity

- Temperature inhomogeneity reflects initial density perturbation on large scales
- Consider a single Fourier moment:



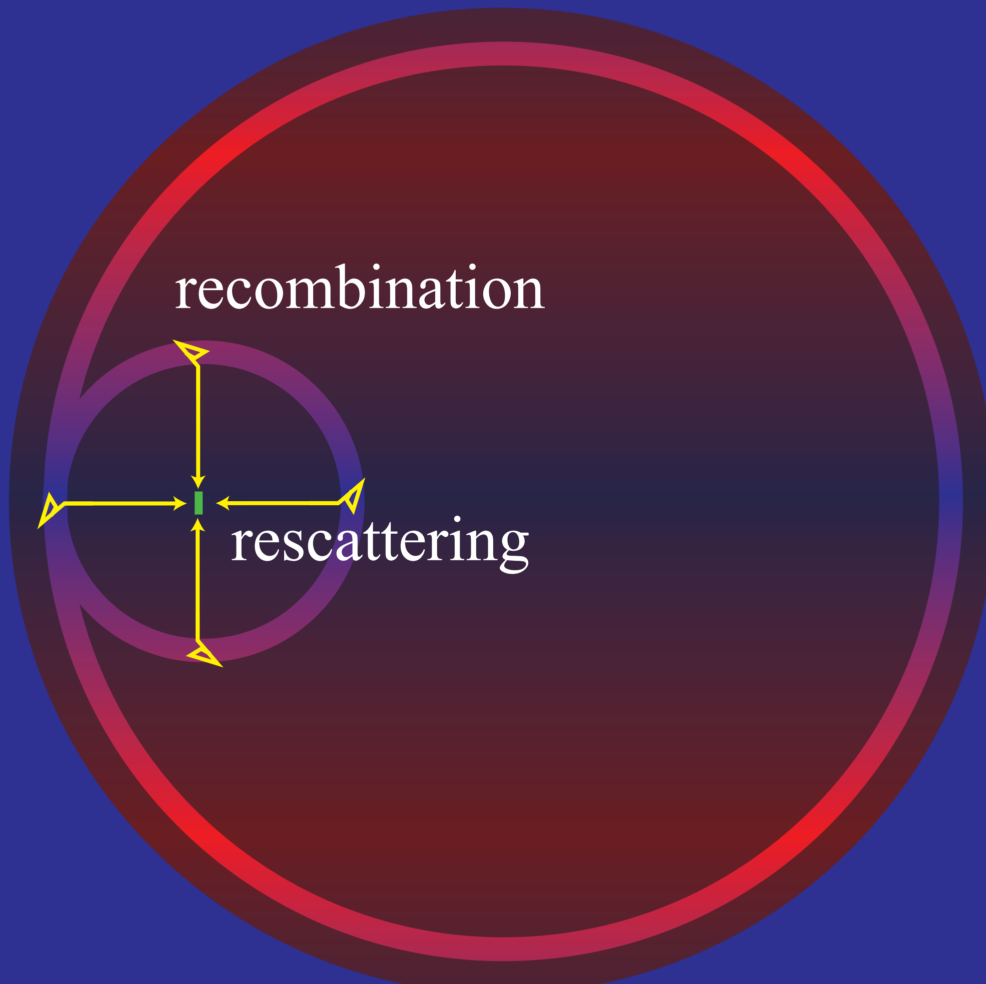
Locally Transparent

- Presently, the matter density is so low that a typical CMB photon will not scatter in a Hubble time (~age of universe)



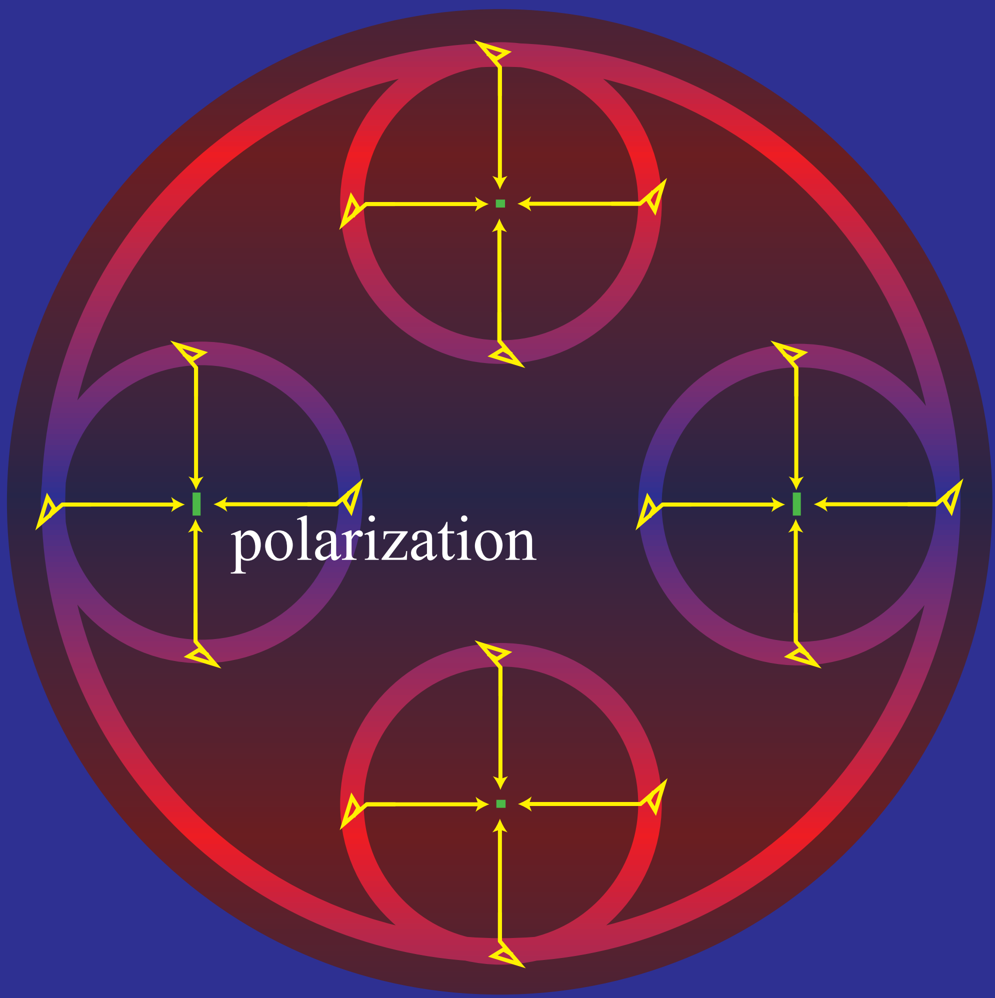
Reversed Expansion

- Free electron density in an ionized medium increases as scale factor a^{-3}; when the universe was a tenth of its current size CMB photons have a finite (~10%) chance to scatter



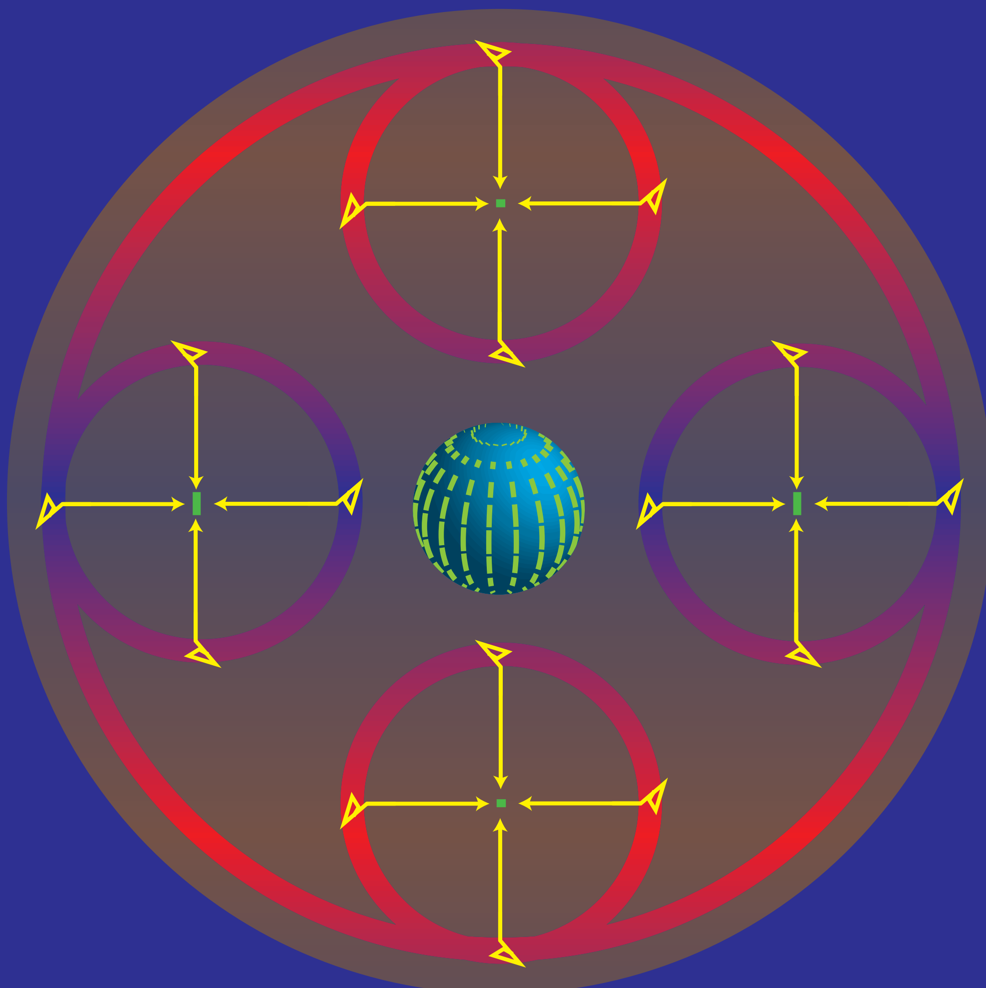
Polarization Anisotropy

- Electron sees the temperature anisotropy on its recombination surface and scatters it into a polarization



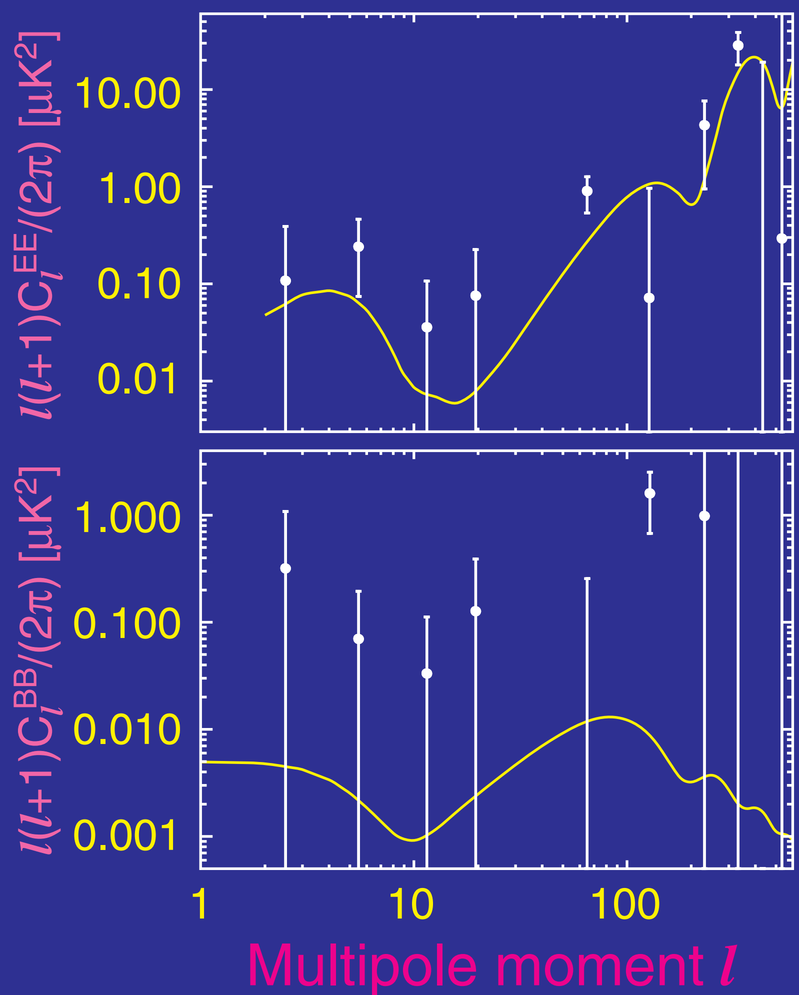
Temperature Correlation

- Pattern correlated with the temperature anisotropy that generates it; here an m=0 quadrupole



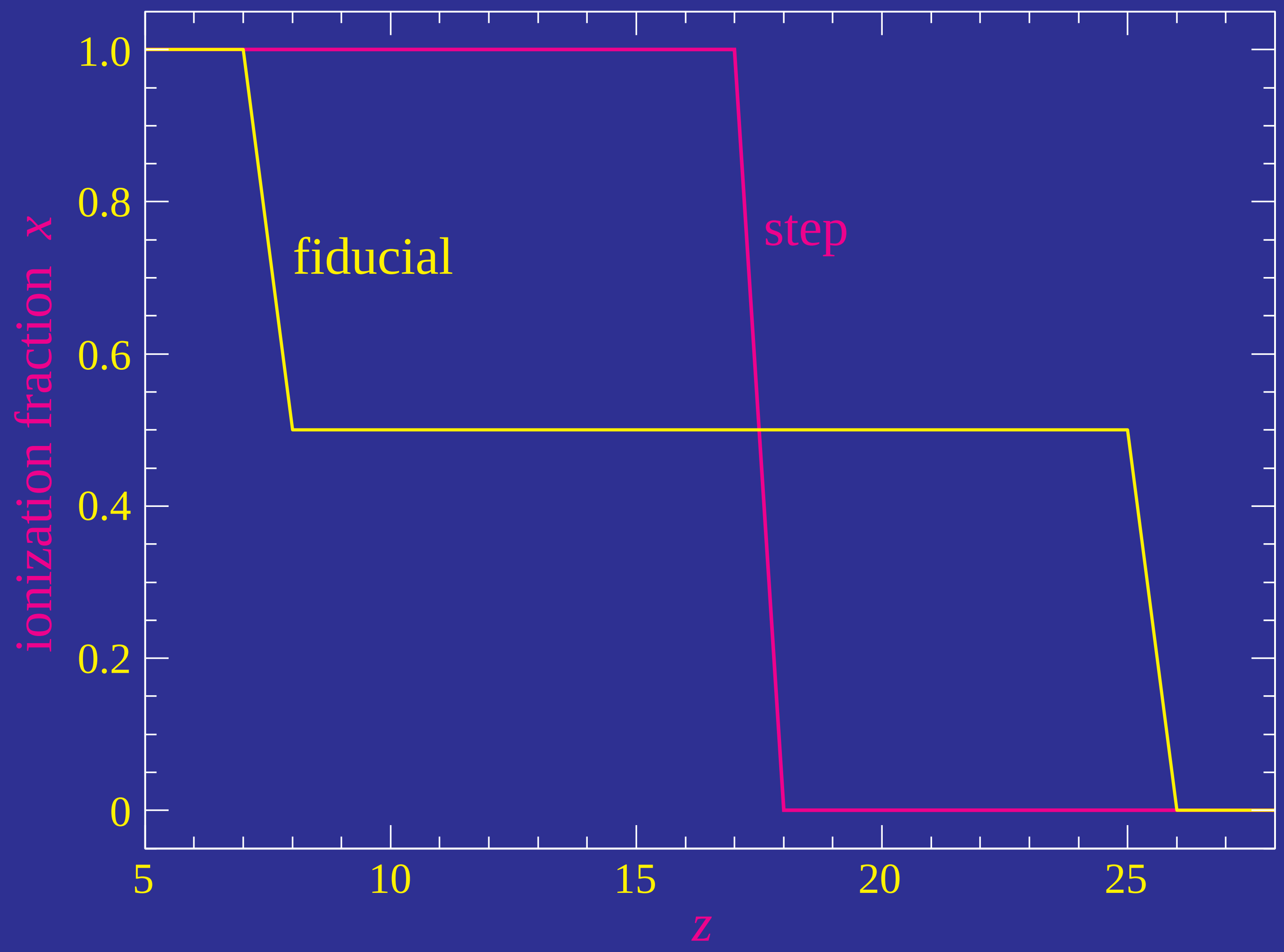
Instantaneous Reionization

- WMAP data constrains optical depth for instantaneous models of τ=0.087±0.017
- Upper limit on gravitational waves weaker than from temperature



Ionization History

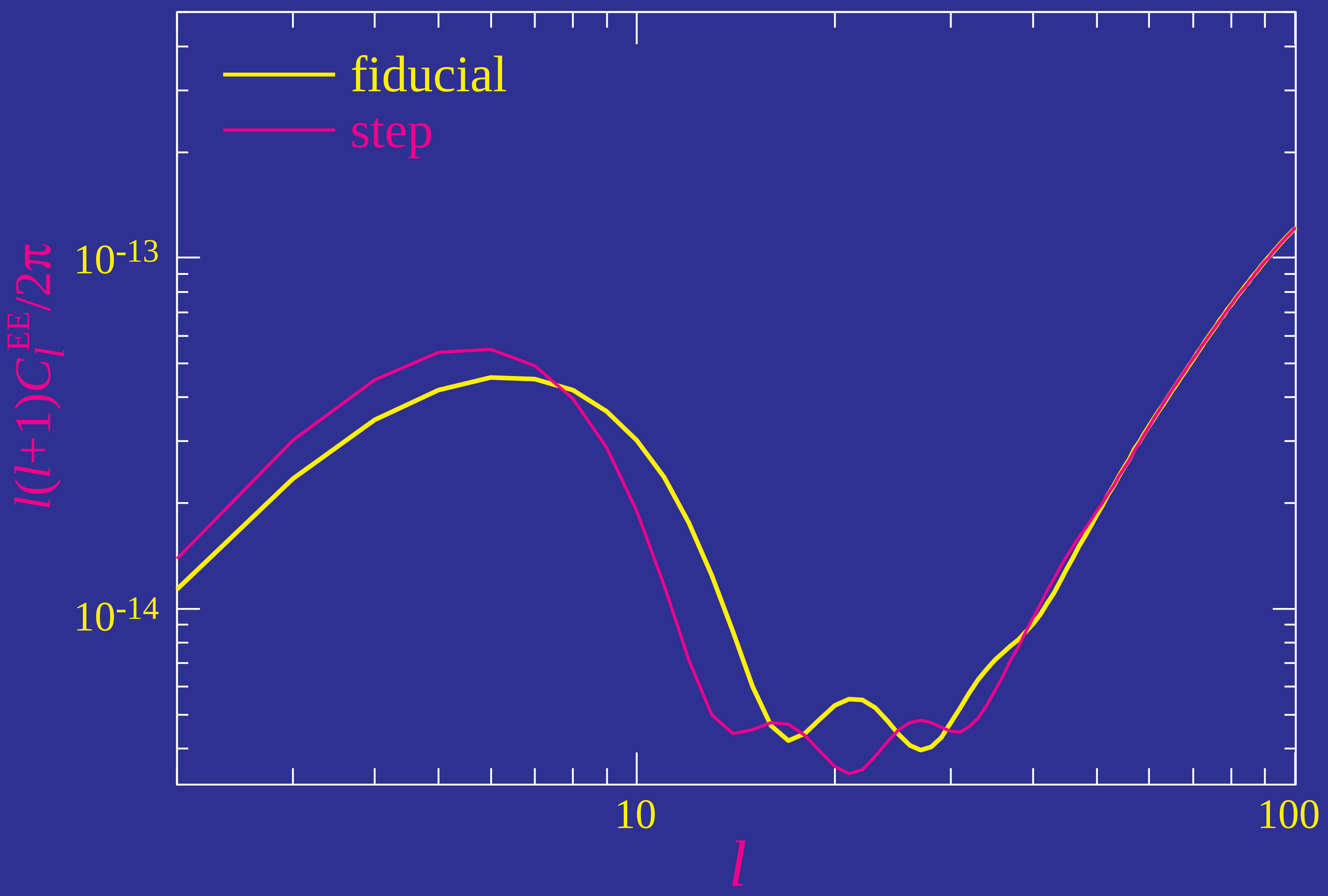
- Two models with same optical depth τ but different ionization history



Kaplinghat et al. (2002); Hu & Holder (2003)

Distinguishable History

- Same optical depth, but different coherence - horizon scale during scattering epoch

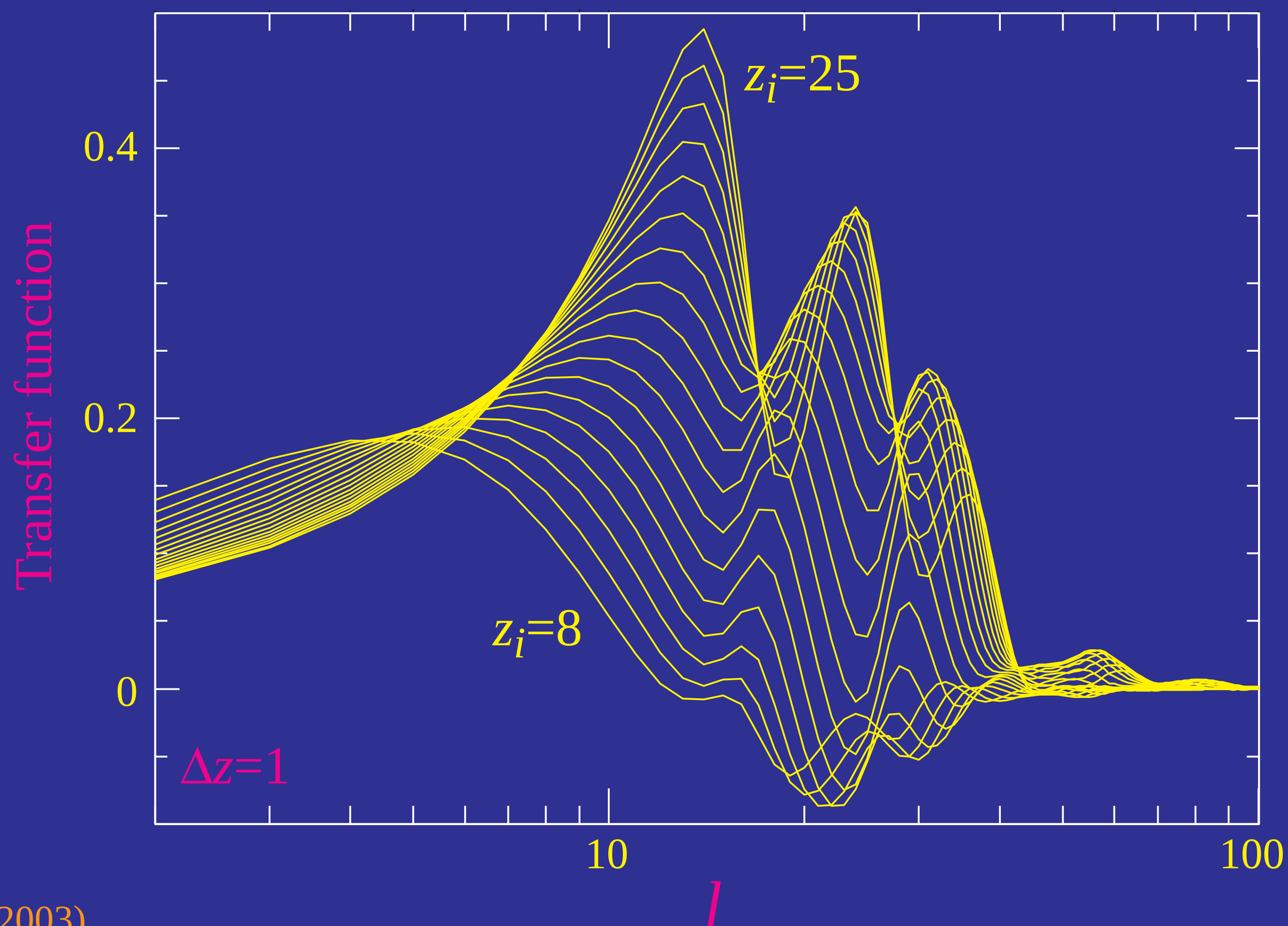


Kaplinghat et al. (2002); Hu & Holder (2003)

Transfer Function

- Linearized response to delta function ionization perturbation

$$T_{\ell i} \equiv \frac{\partial \ln C_\ell^{EE}}{\partial x(z_i)}, \qquad \delta C_\ell^{EE} = C_\ell^{EE} \sum_i T_{\ell i} \delta x(z_i)$$

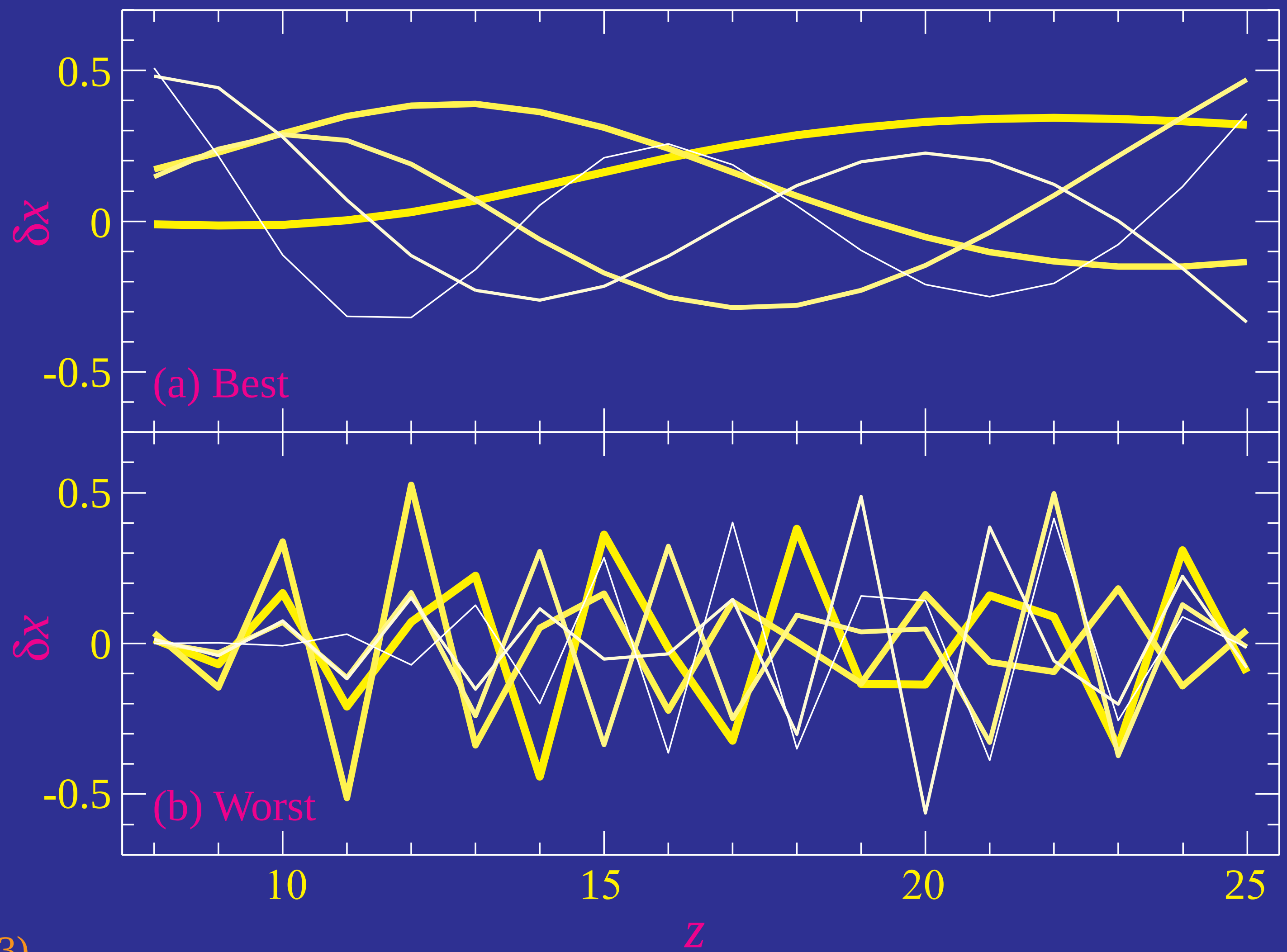


Hu & Holder (2003)

Principal Components

- Eigenvectors of the Fisher Matrix

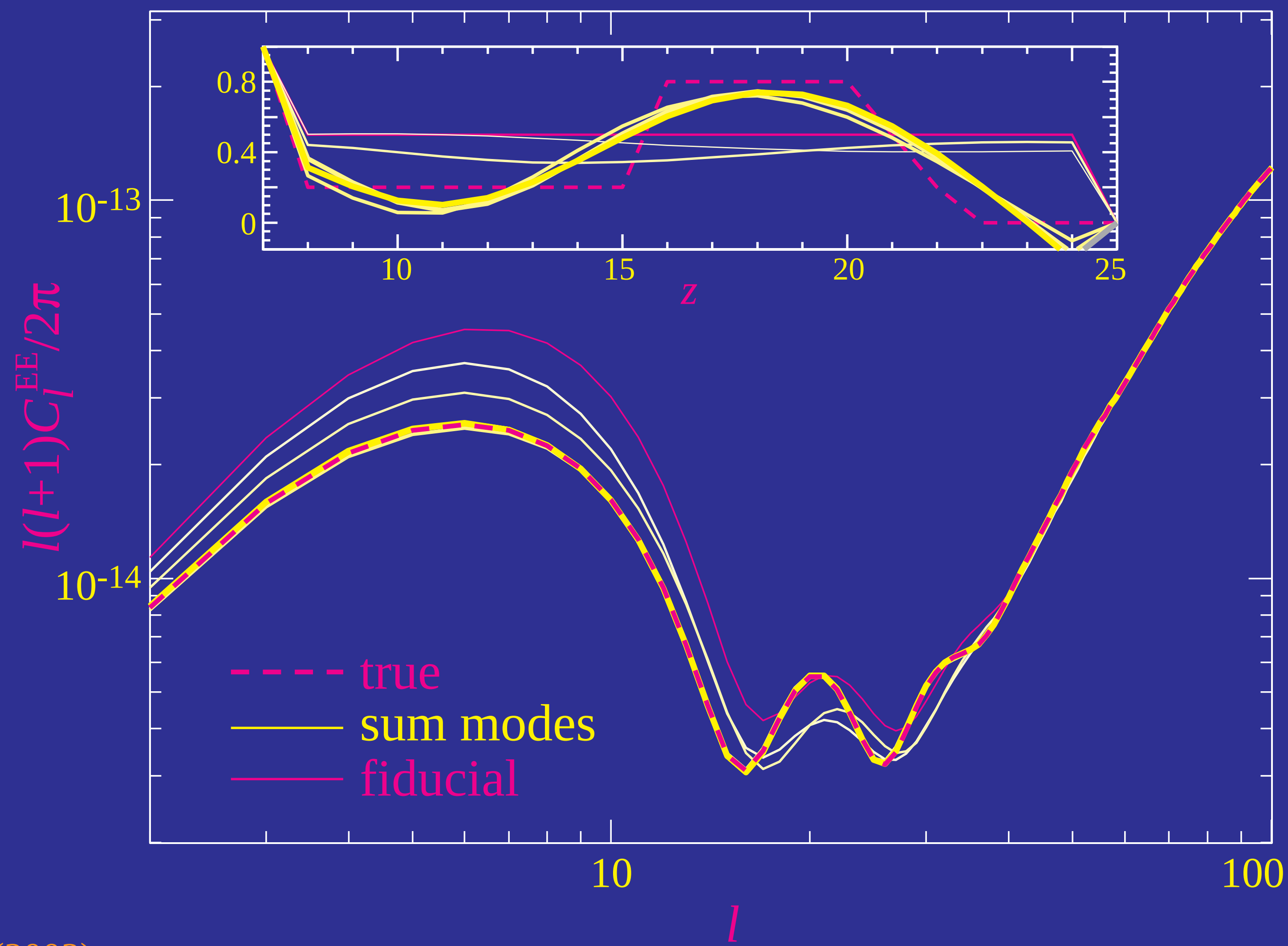
$$F_{ij} \equiv \sum_{\ell} (\ell + 1/2) T_{\ell i} T_{\ell j} = \sum_{\mu} S_{i\mu} \sigma_{\mu}^{-2} S_{j\mu}$$



Hu & Holder (2003)

Representation in Modes

- Reproduces the power spectrum with sum over >3 modes
  more generally 5 modes suffices: e.g. total τ=0.1375 vs 0.1377

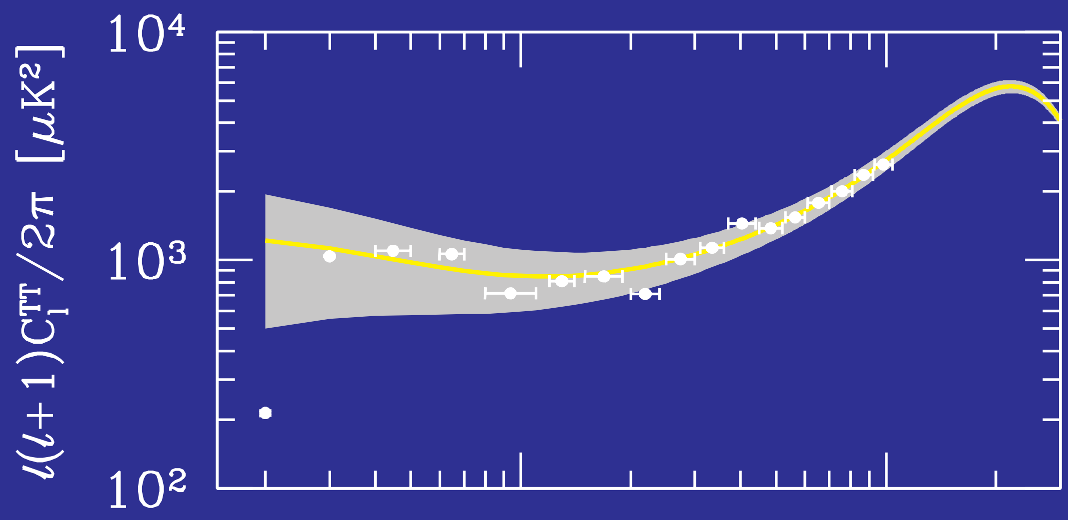


Hu & Holder (2003)

Large Scale Anomalies

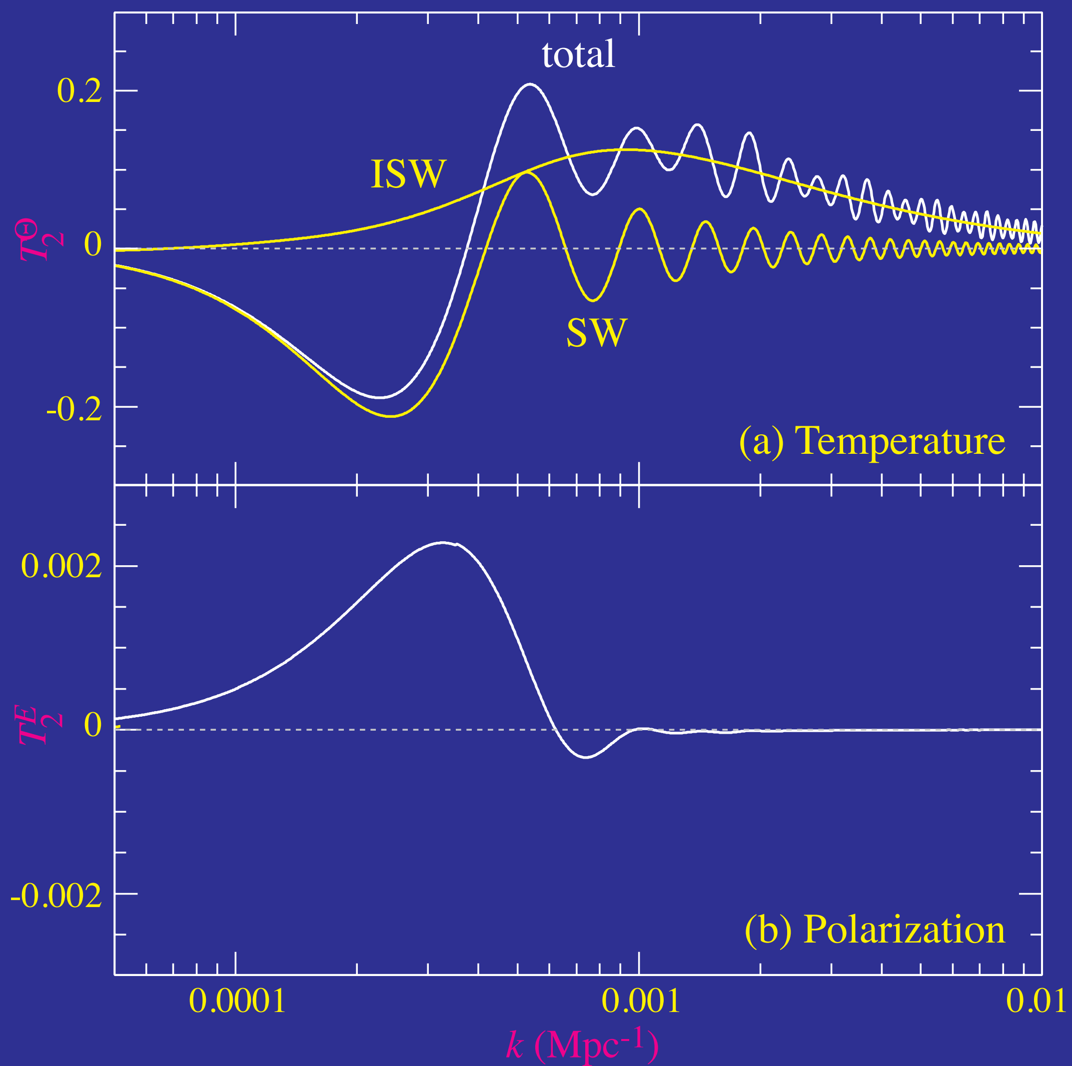
Low Quadrupole

- Temperature quadrupole is low compared with best fit ΛCDM model



Quadrupole Origins

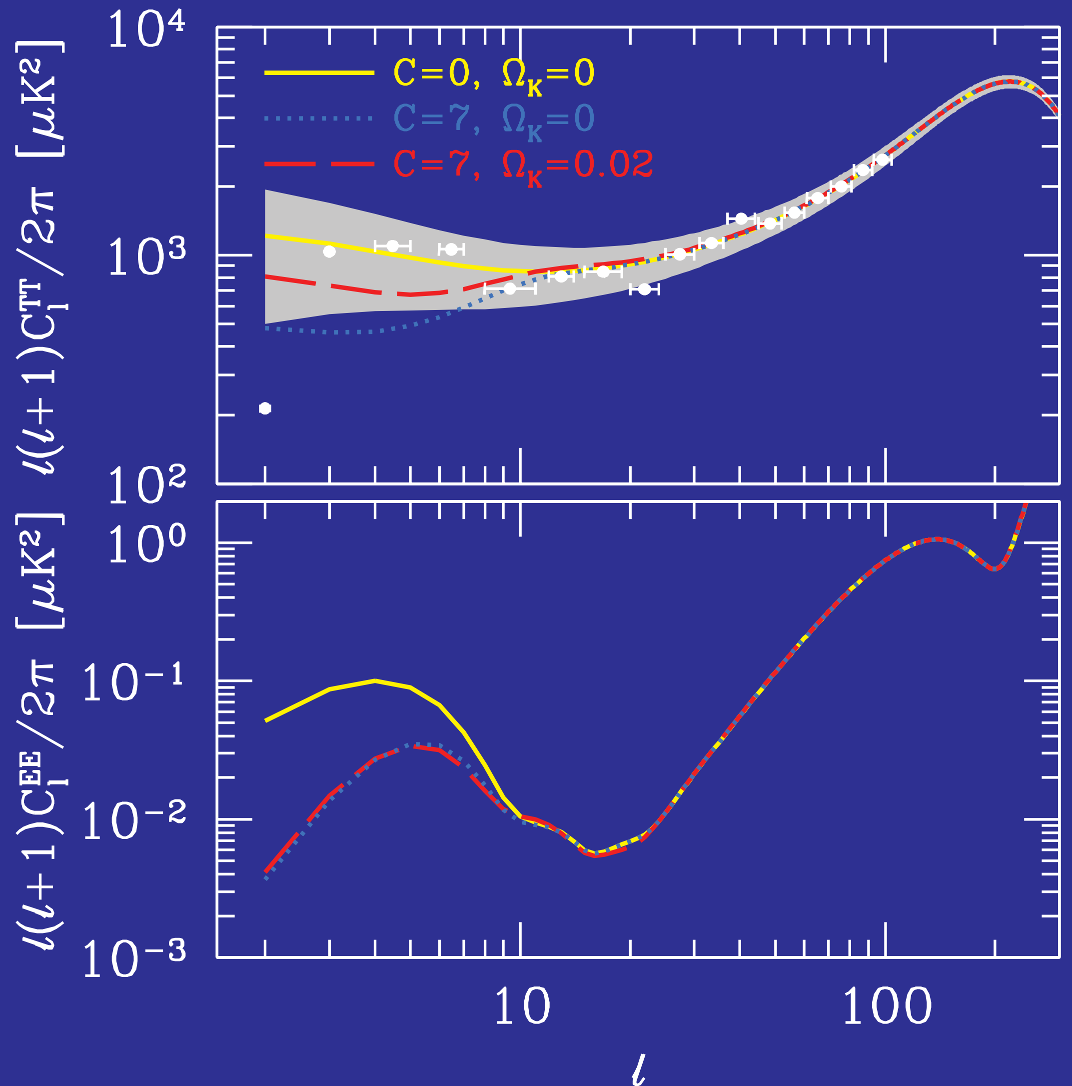
- Transfer function for the quadrupole



Gordon & Hu (2004)

Horizon-Scale Power

- Polarization is a robust indicator of horizon scale power and disfavors suppression as explanation of low quadrupole independently of ionization or acceleration model



Mortonson & Hu (2009)

Quadrupole Origins

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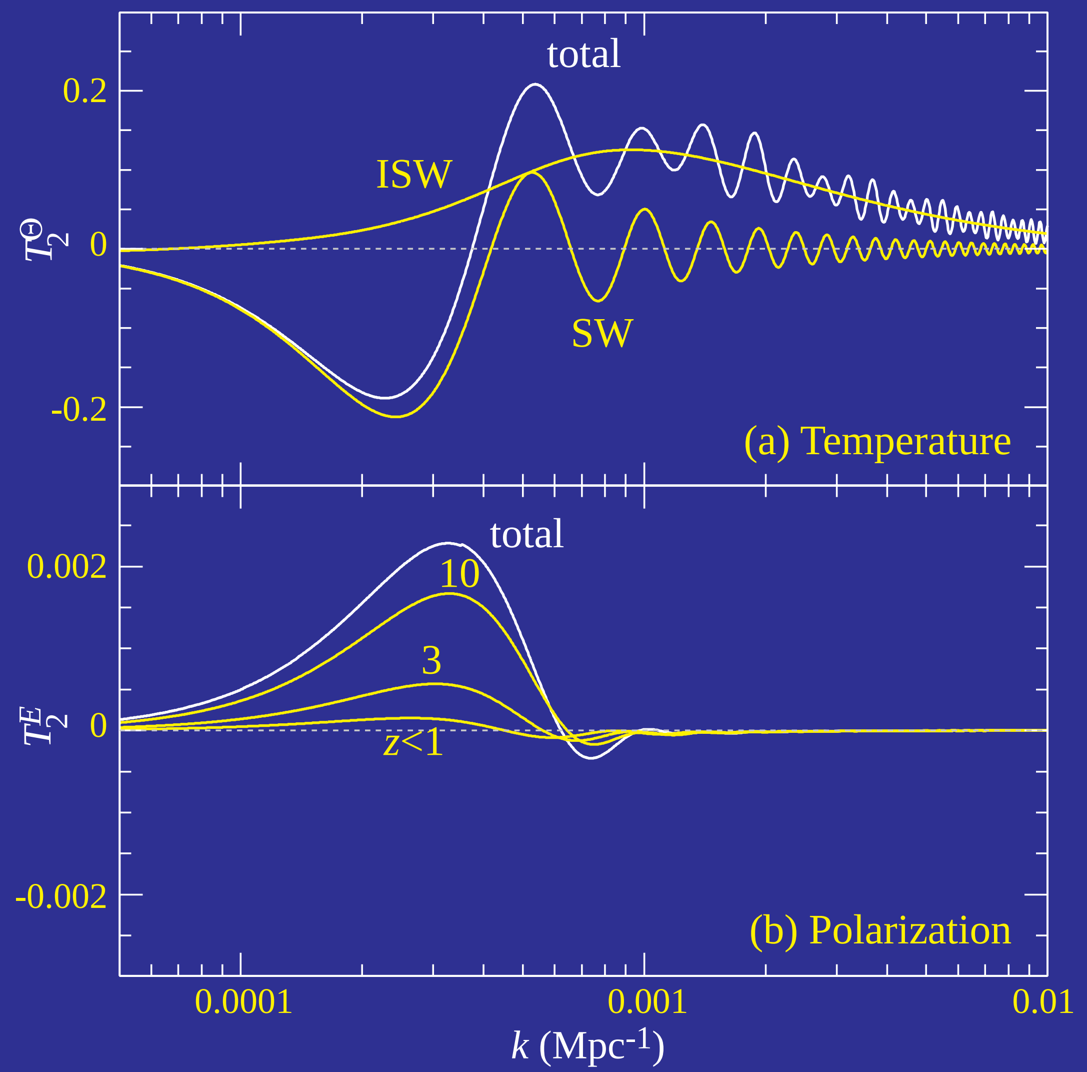
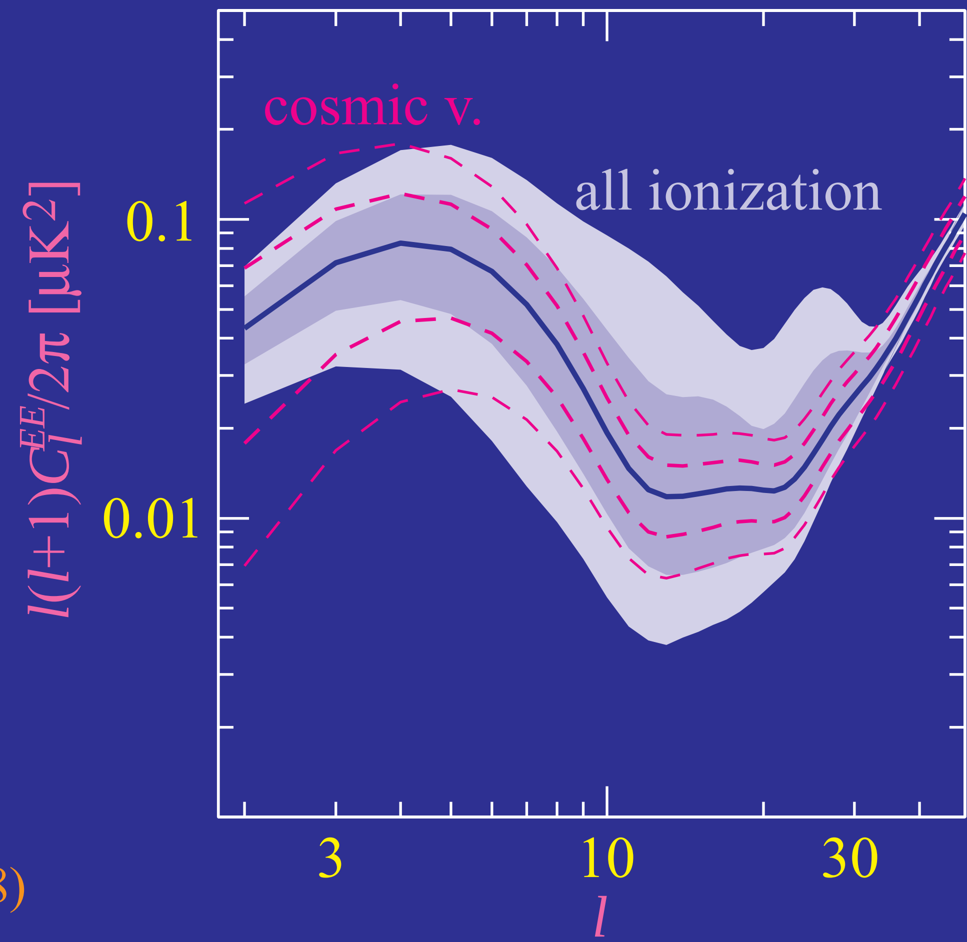


Gordon & Hu (2004)

Model-Independent Reionization

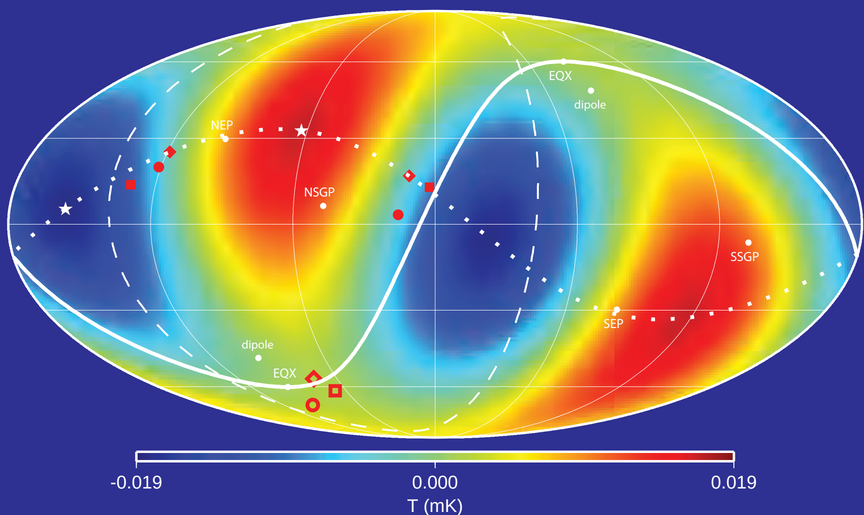
- All possible ionization histories at $z<30$
- Detections at $20<l<30$ required to further constrain general ionization which widens the τ-n_s degeneracy allowing $n_s=1$
- Quadrupole & octopole predicted to better than cosmic variance test ΛCDM for anomalies

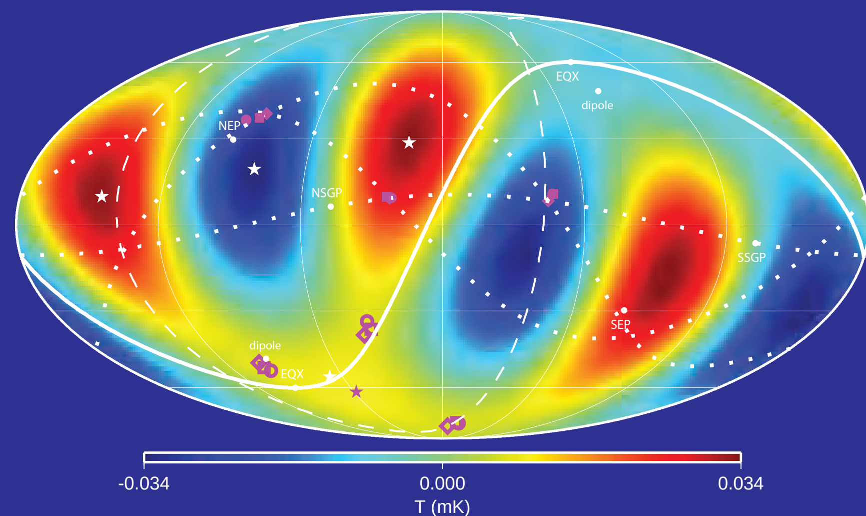


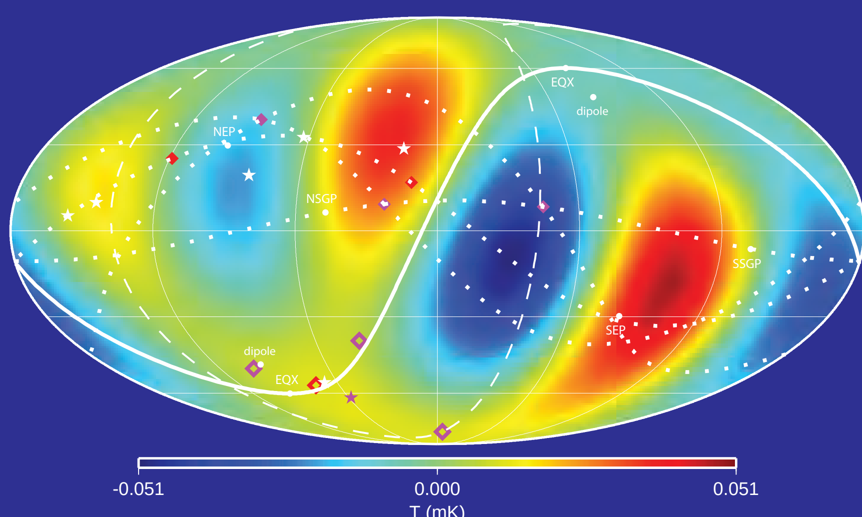
Mortonson & Hu (2008)

Large Angle Anomalies

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





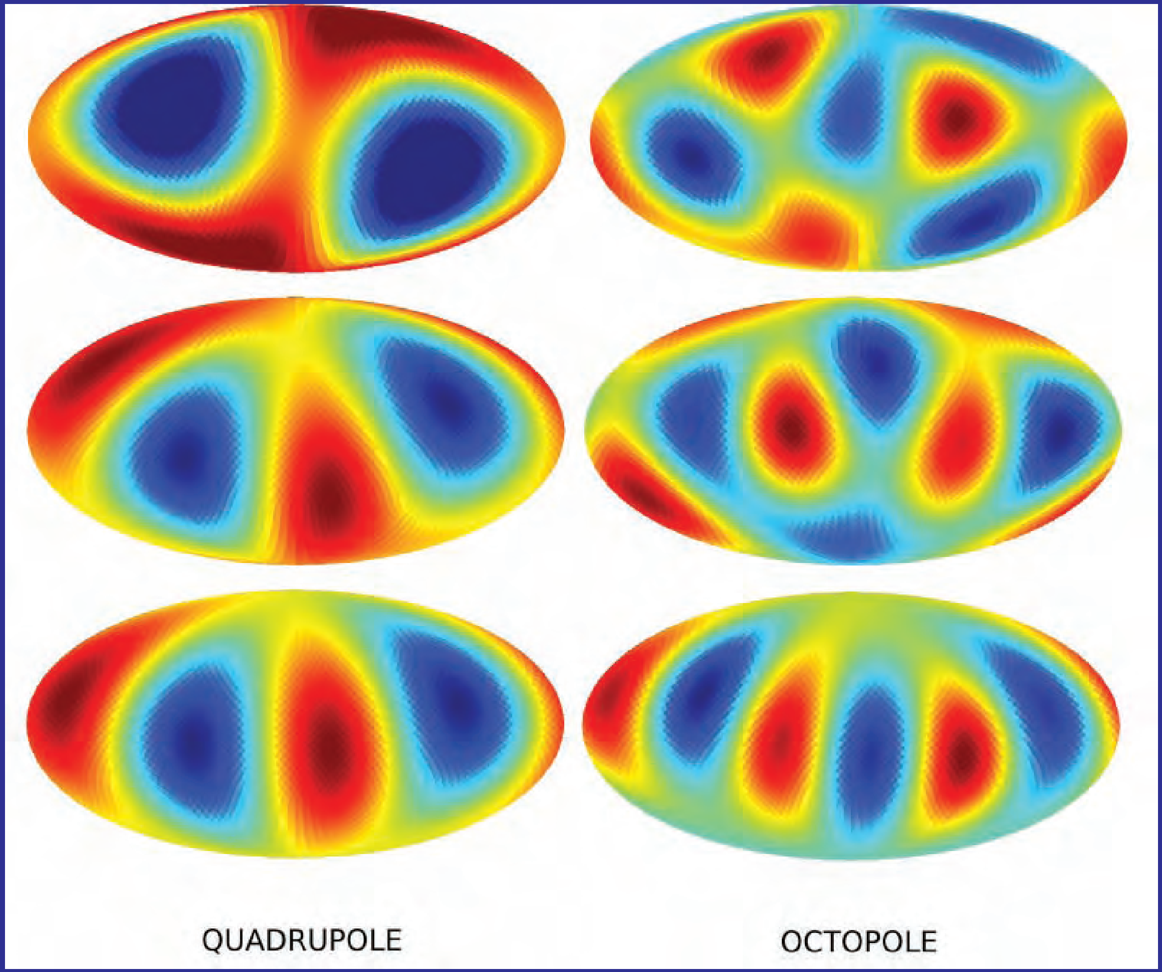


Copi et al (2006)

Polarization Tests

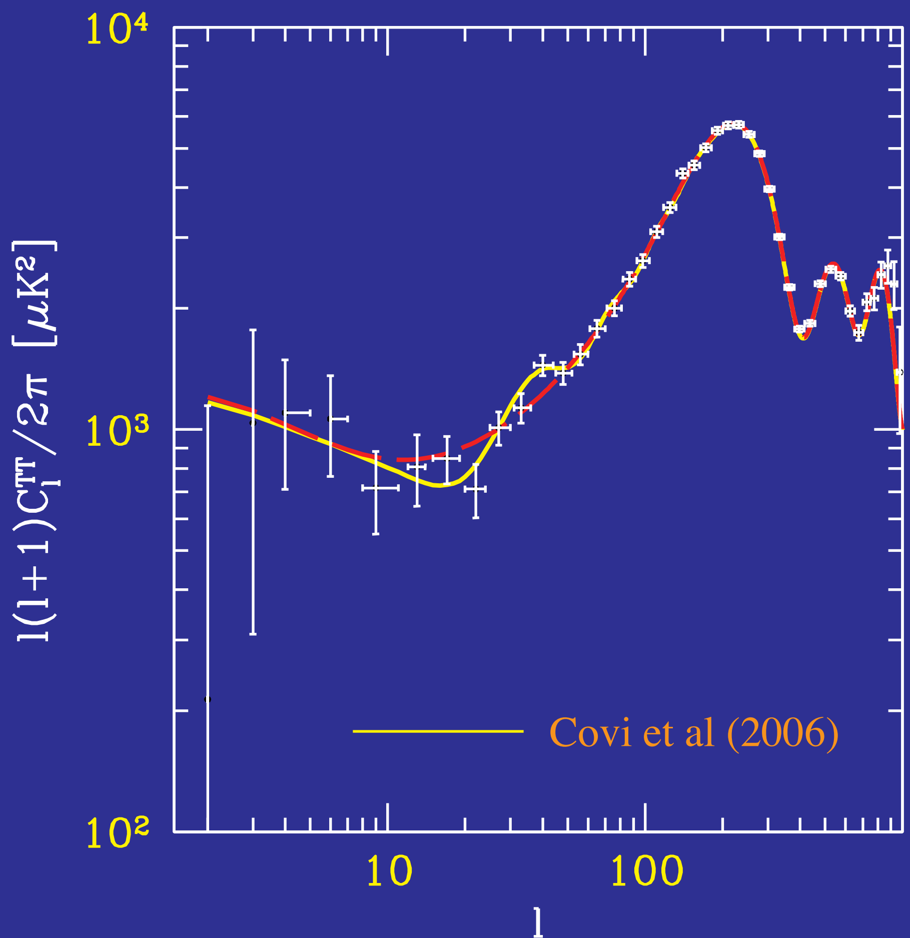
- Matching polarization anomalies if cosmological

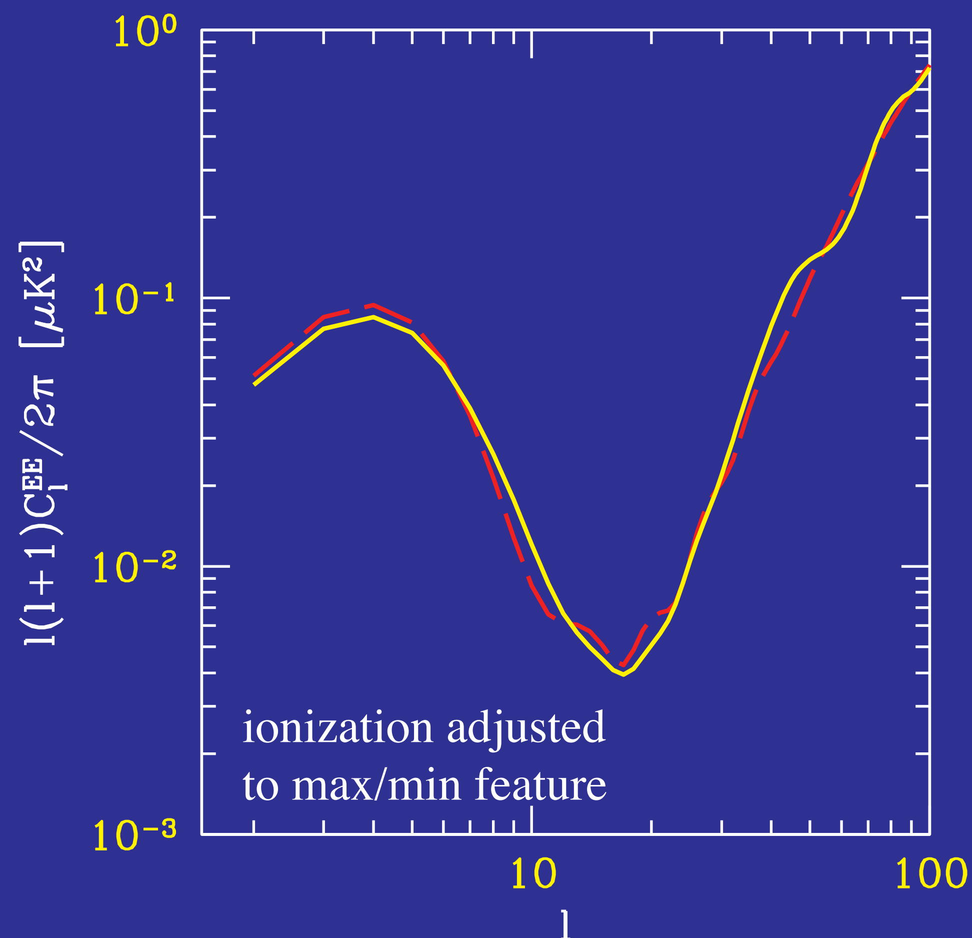
Dvorkin, Peiris, Hu (2007)



Polarization Bumps

- If features in the temperature spectrum reflect features in the power spectrum (inflationary potential), reflected in polarization with little ambiguity from reionization





Mortonson et al (2009)

Inflation

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 $f_{\rm nl}$>few would rule out single field slow roll)

Inflationary Observables

- Curvature Power Spectrum:

$$\Delta^2_{\mathcal{R}} \approx \frac{8\pi G}{2}\frac{1}{\epsilon}\left(\frac{H}{2\pi}\right)^2 , \quad \epsilon = \frac{1}{2}\frac{1}{8\pi G}\left(\frac{V'}{V}\right)^2$$

- Tilt

$$\frac{d\ln\Delta^2_{\mathcal{R}}}{d\ln k} = n_S - 1 = -4\epsilon - 2\delta$$

where

$$\delta = \epsilon - \frac{1}{8\pi G}\frac{V''}{V}$$

So for featureless potentials e.g. monomial ϕ^n, $\epsilon \sim |\delta|$

- Running $dn_S/d\ln k$ second order

Inflationary Observables

- Gravitational Wave (Tensor) Power Spectrum:

$$\Delta^2_{+,\times} = 16\pi G \left(\frac{H}{2\pi}\right)^2$$

reflects energy scale of inflation $H^2 \propto V \equiv E_i^4$

$$\Delta B_{\rm peak} \approx 0.024 \left(\frac{E_i}{10^{16}{\rm GeV}}\right)^2 \mu{\rm K}$$

- Tensor-Scalar Ratio, Tilt:

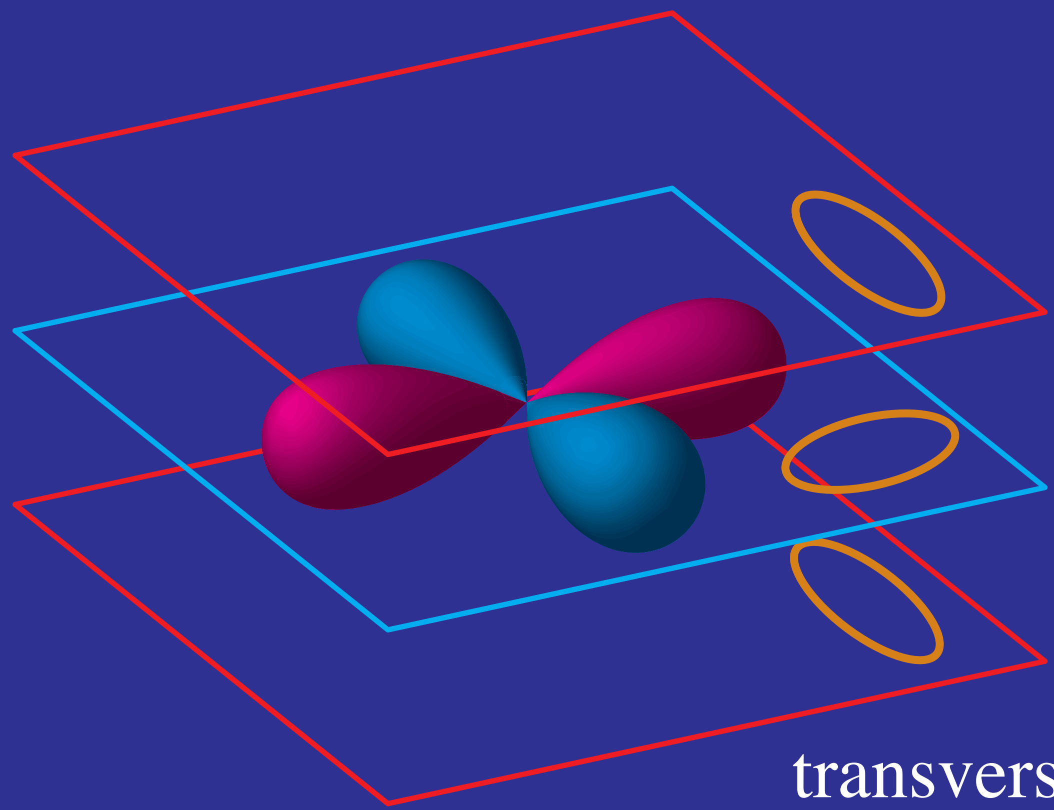
$$r \equiv 4\frac{\Delta^2_+}{\Delta^2_{\mathcal{R}}} = 16\epsilon\,, \qquad \frac{d\ln\Delta^2_+}{d\ln k} \equiv n_T = 2\frac{d\ln H}{d\ln k} = -2\epsilon$$

- Consistency:

$$r = -8n_T$$

Quadrupoles from Gravitational Waves

- Transverse-traceless distortion provides temperature quadrupole
- Gravitational wave polarization picks out direction transverse to wavevector

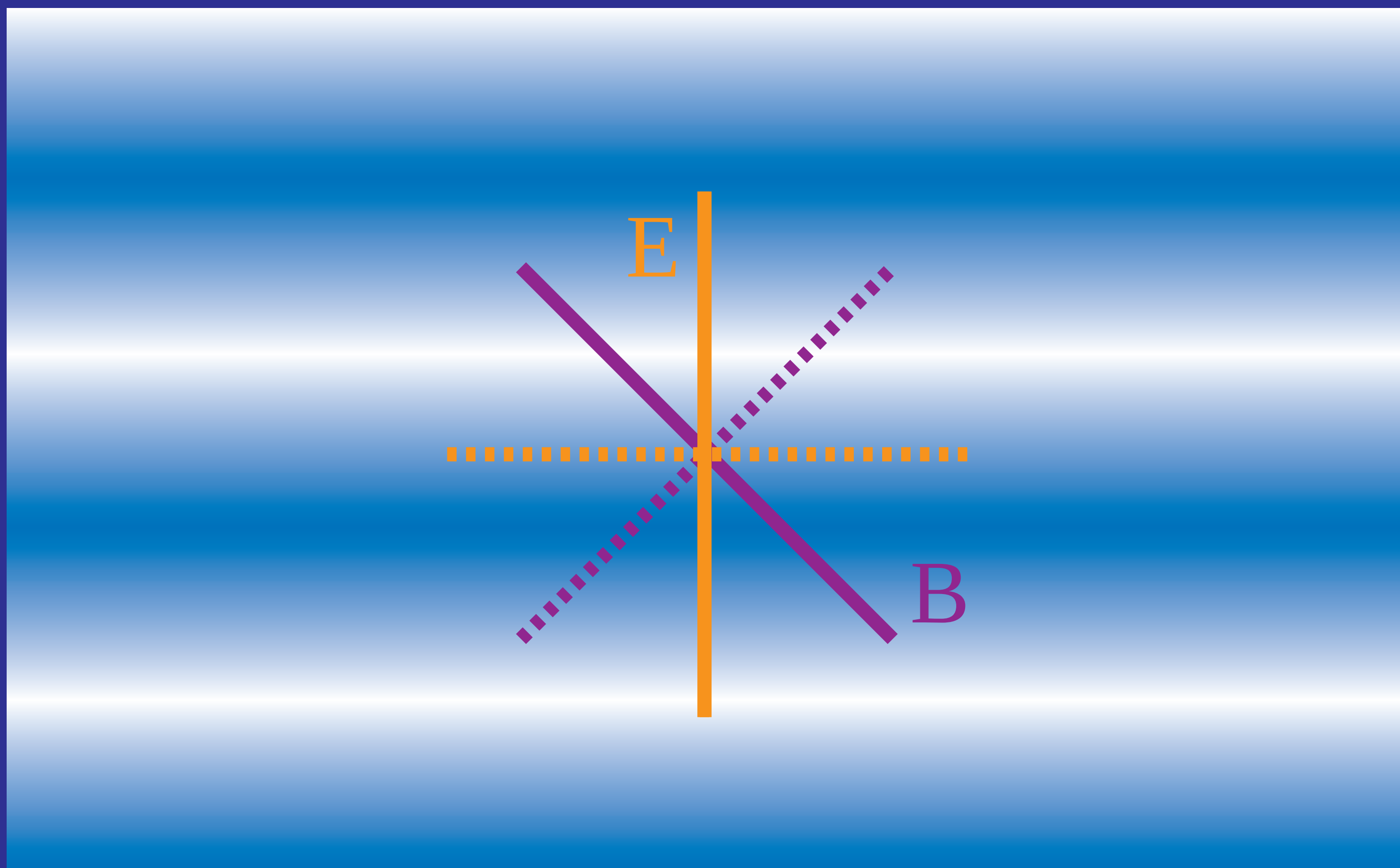


transverse-traceless
distortion

Electric & Magnetic Polarization

(a.k.a. gradient & curl)

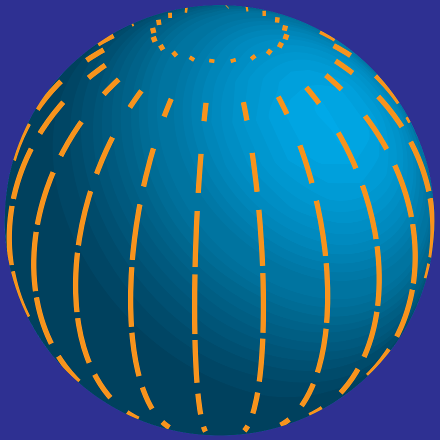
- Alignment of principal vs polarization axes
  (curvature matrix vs polarization direction)



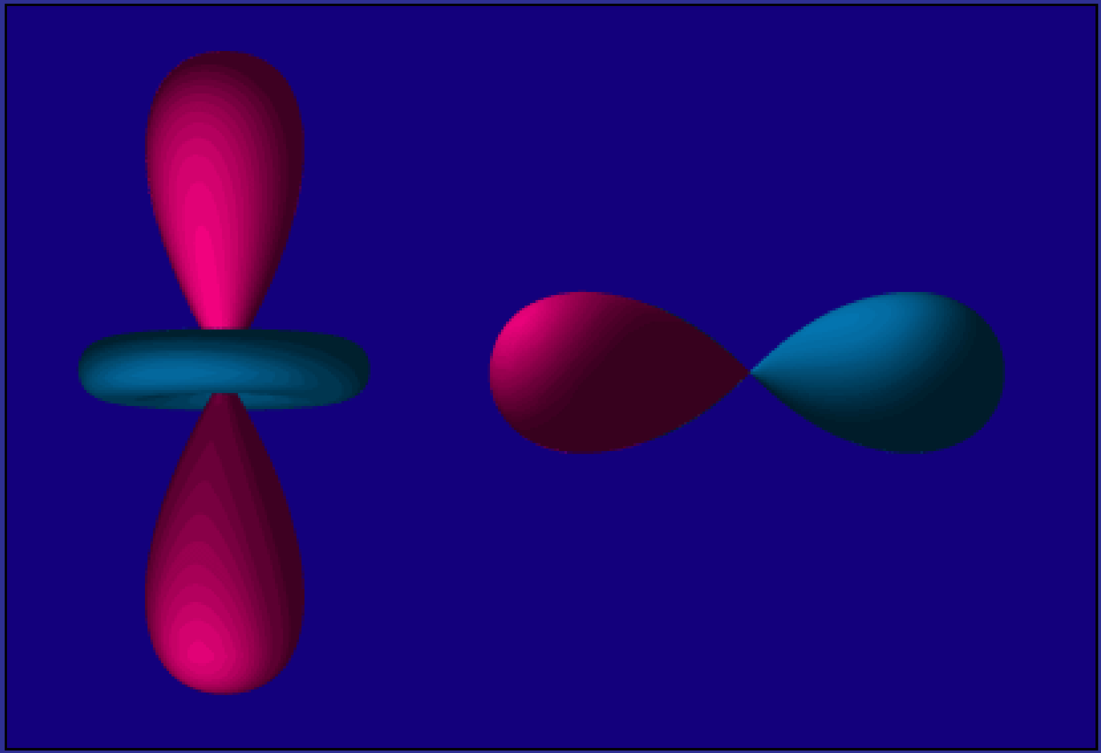
Kamionkowski, Kosowsky, Stebbins (1997)
Zaldarriaga & Seljak (1997)

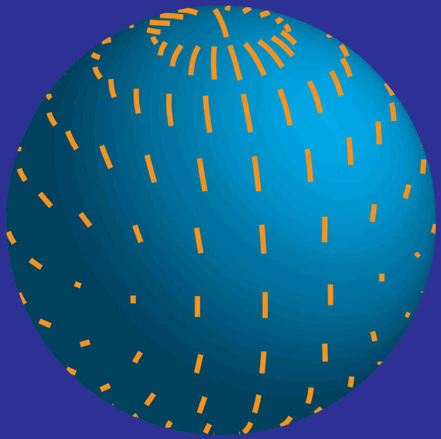
Gravitational Wave Pattern

- Projection of the quadrupole anisotropy gives polarization pattern
- Transverse polarization of gravitational waves breaks azimuthal symmetry



density perturbation

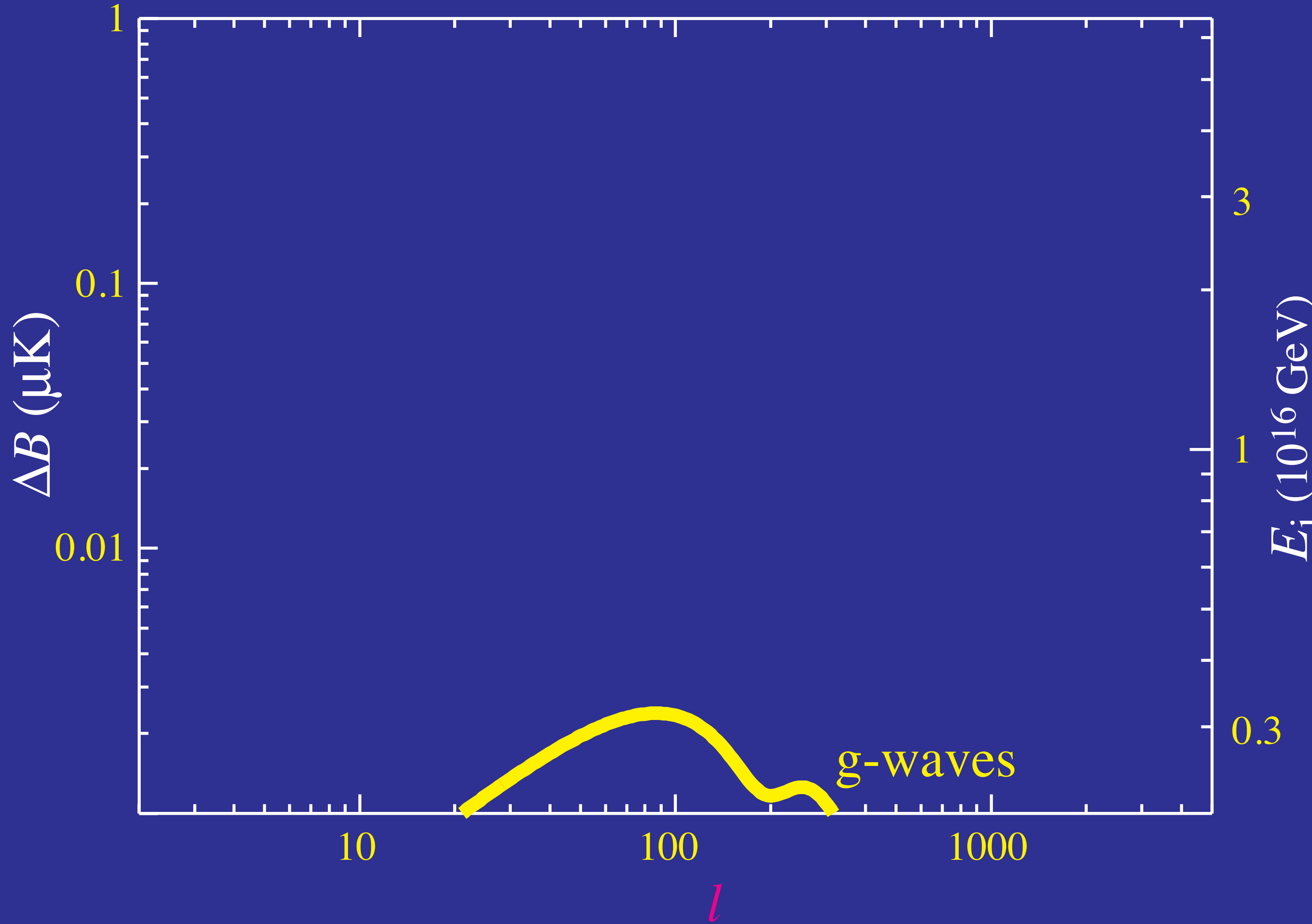




gravitational wave

Energy Scale of Inflation

- Amplitude of B-mode peak scales as square of energy scale (Hubble parameter) during inflation, power as E_i^4
- Good: upper limits are at GUT scale. Bad: secondaries & foregrounds



Large Field, Small Field Models

- For detectable gravitational waves $r > 0.01$, scalar field must roll by order $M_{\rm pl} = (8\pi G)^{-1/2}$

$$\frac{d\phi}{dN} = \frac{d\phi}{d\ln a} = \frac{d\phi}{dt}\frac{1}{H}$$

- The larger ϵ is the more the field rolls in an e-fold

$$\epsilon = \frac{r}{16} = \frac{3}{2V}\left(H\frac{d\phi}{dN}\right)^2 = \frac{8\pi G}{2}\left(\frac{d\phi}{dN}\right)^2$$

- Observable scales span $\Delta N \sim 5$ so

$$\Delta\phi > 5\frac{d\phi}{dN} = 5\left(\frac{r}{8}\right)^{1/2} M_{\rm pl} \approx 0.2\left(\frac{r}{0.01}\right)^{1/2} M_{\rm pl}$$

- Does this make sense as an effective field theory? Lyth (1997)
- Small field models where ϕ near maximum more reasonable?
- Large field existence proof: monodromy Silverstein & Westphal (2008) ...theorists running around in circles...

Inflation Present

- Tilt indicates that one of the slow roll parameters finite (ignoring exotic high-z reionization)
- Upper limit on gravity waves put an upper limit on V'/V and hence an upper limit on how far the inflaton rolls

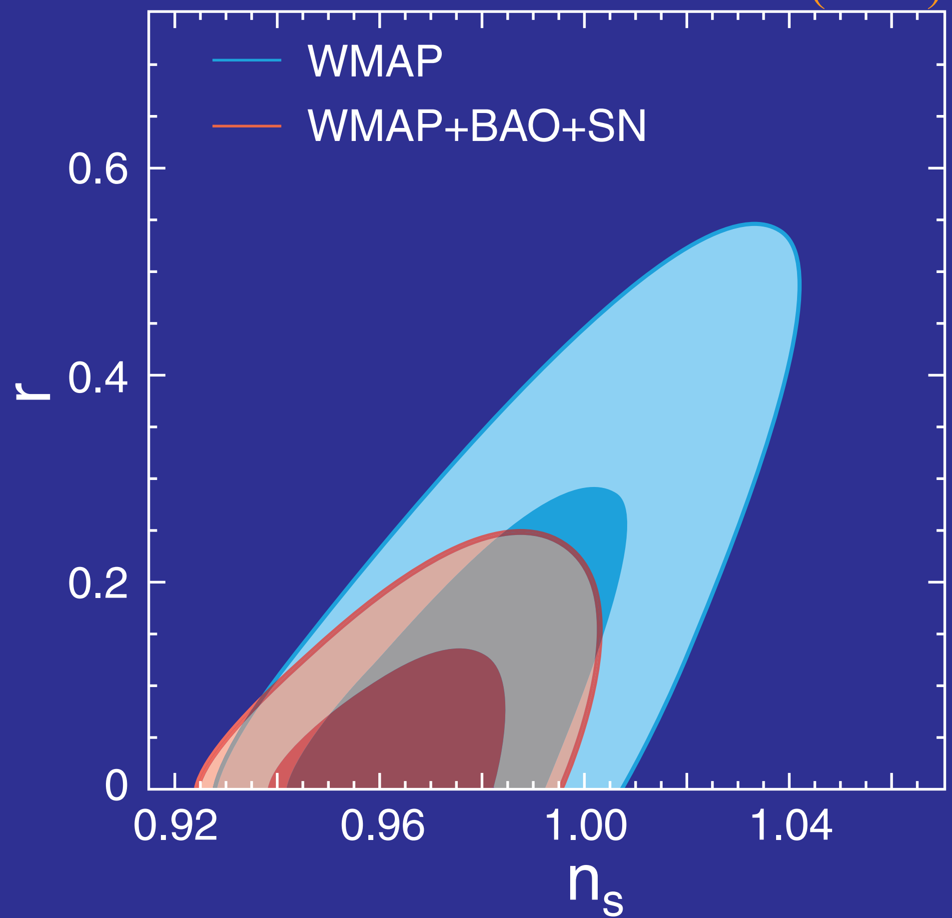
- Constraints in the r-n_s plane test classes of models
- Given functional form of V, constraints on the flatness of potential when the horizon left the horizon predict too many (or few) efolds of further inflation

- Non-Gaussian fluctuations at f_{nl}~50?
- Glitches and large scale anomalies

Inflationary Constraints

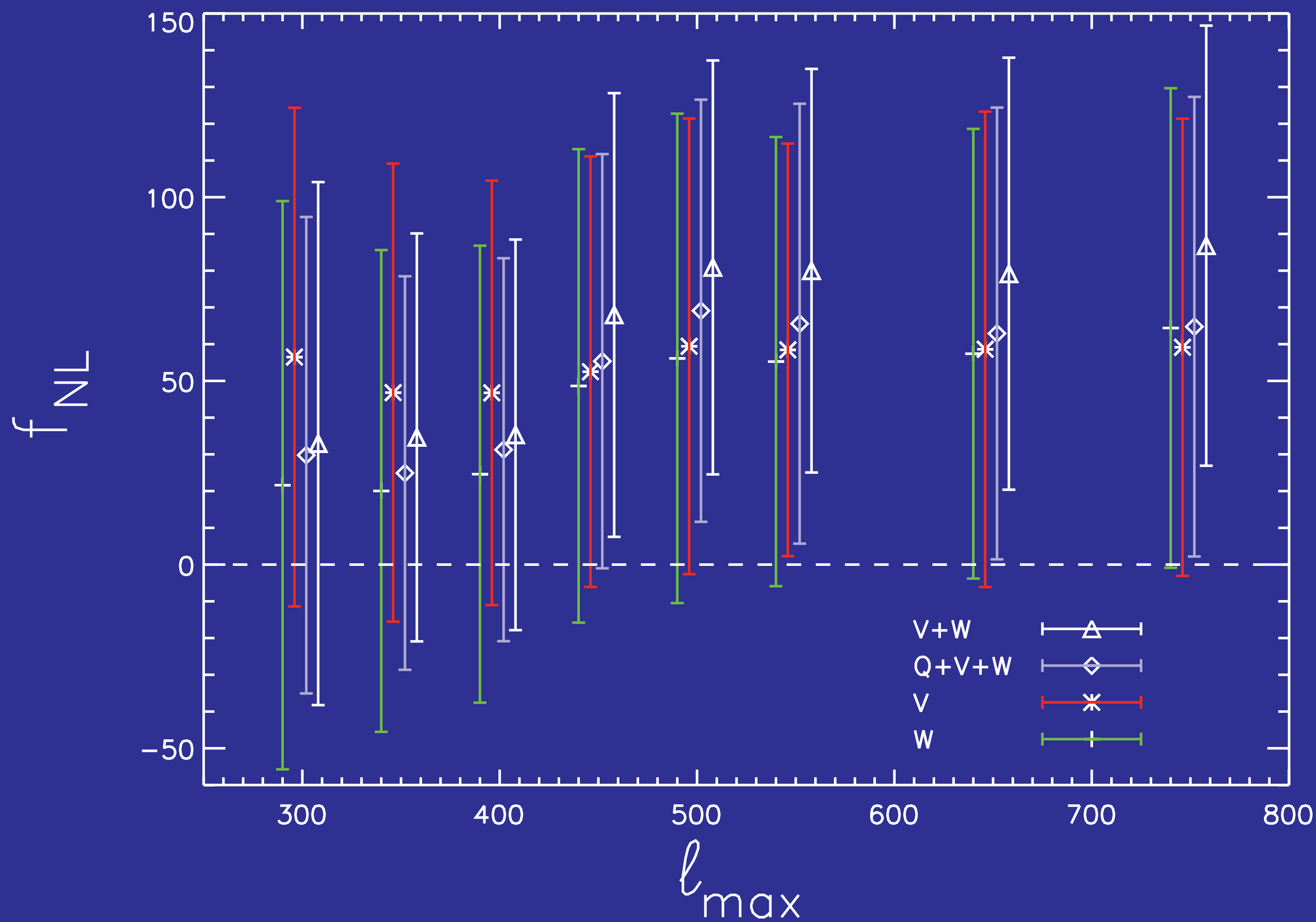
- Tilt mildly favored over tensors as explaining small scale suppression
- Specific models of inflation relate r-n_s through V', V''
- Small tensors and n_s~1 may make inflation continue for too many efolds

Komatsu et al (2008)



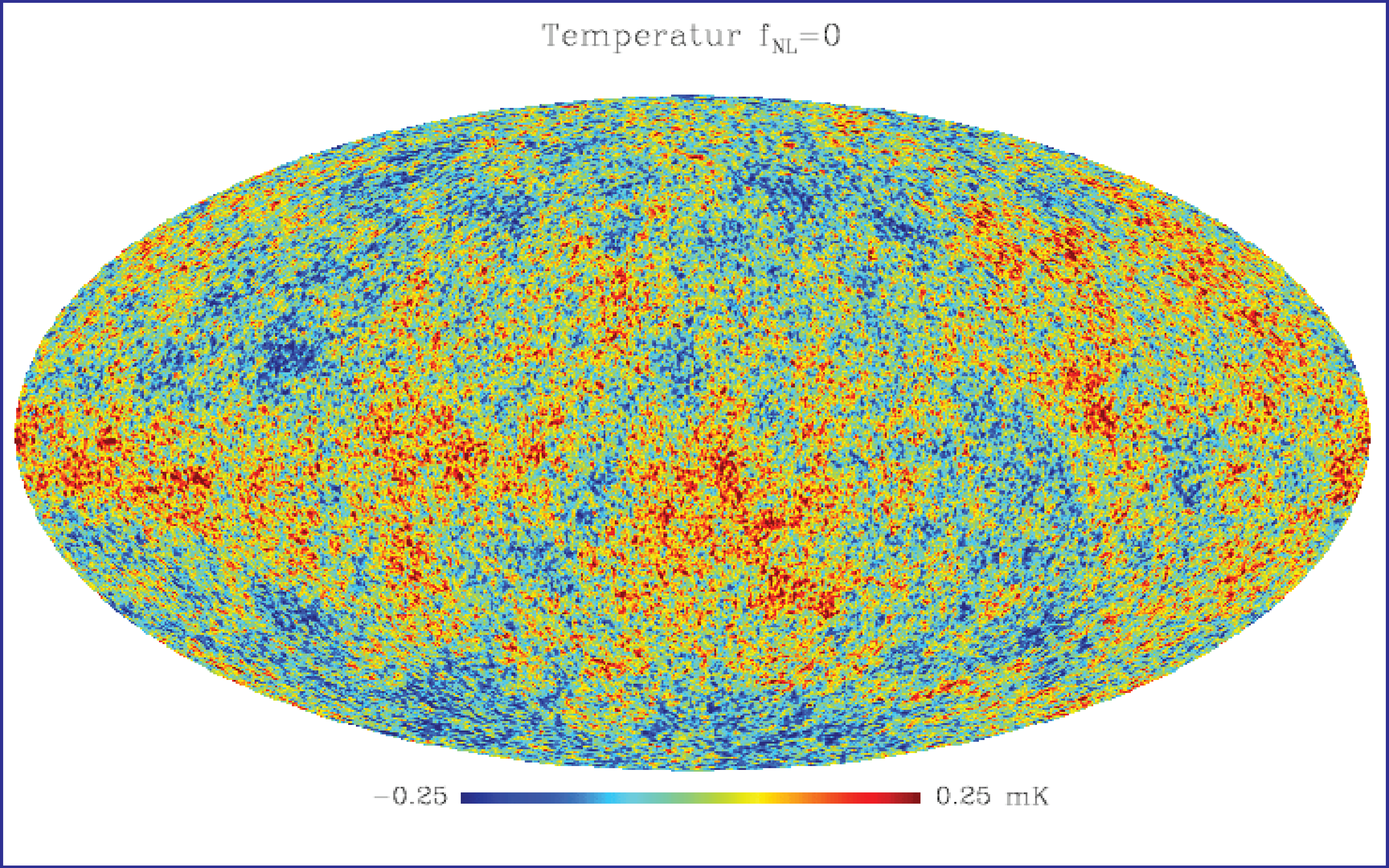
f_{nl}

- Local second order non-Gaussianity: $\Phi_{nl}=\Phi+f_{nl}(\Phi^2-\langle\Phi^2\rangle)$
- WMAP3 Kp0+: $27<f_{nl}<147$ (95% CL) (Yadav & Wandelt 2007)
- WMAP5 opt: $-4<f_{nl}<80$ (95% CL) (Smith, Senatore & Zaldarriaga 2009)



Local Non-Gaussianity

- Local non-Gaussianity couples long to short wavelength fluctuations



Ligouri et al (2007)

Local Non-Gaussianity

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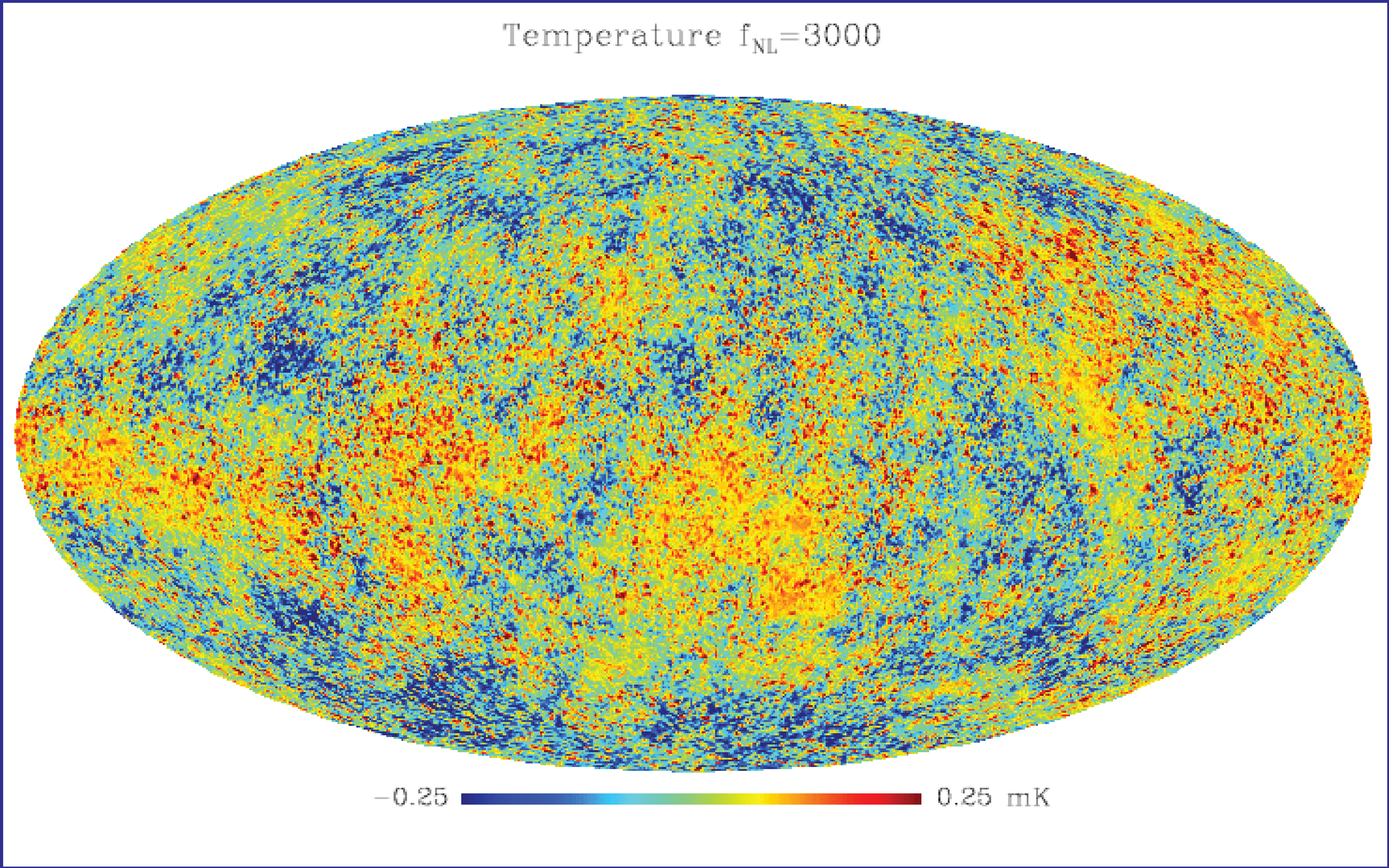


Ligouri et al (2007)

Inflation Future

- Planck can test Gaussianity down to $f_{\rm nl}$~few and make a high significance detection if $f_{\rm nl}$~50
- Planck will provide a high significance measurement of tilt (n_S-1)
- Planck will test constancy of tilt - significant deviation would rule out all standard slow roll models

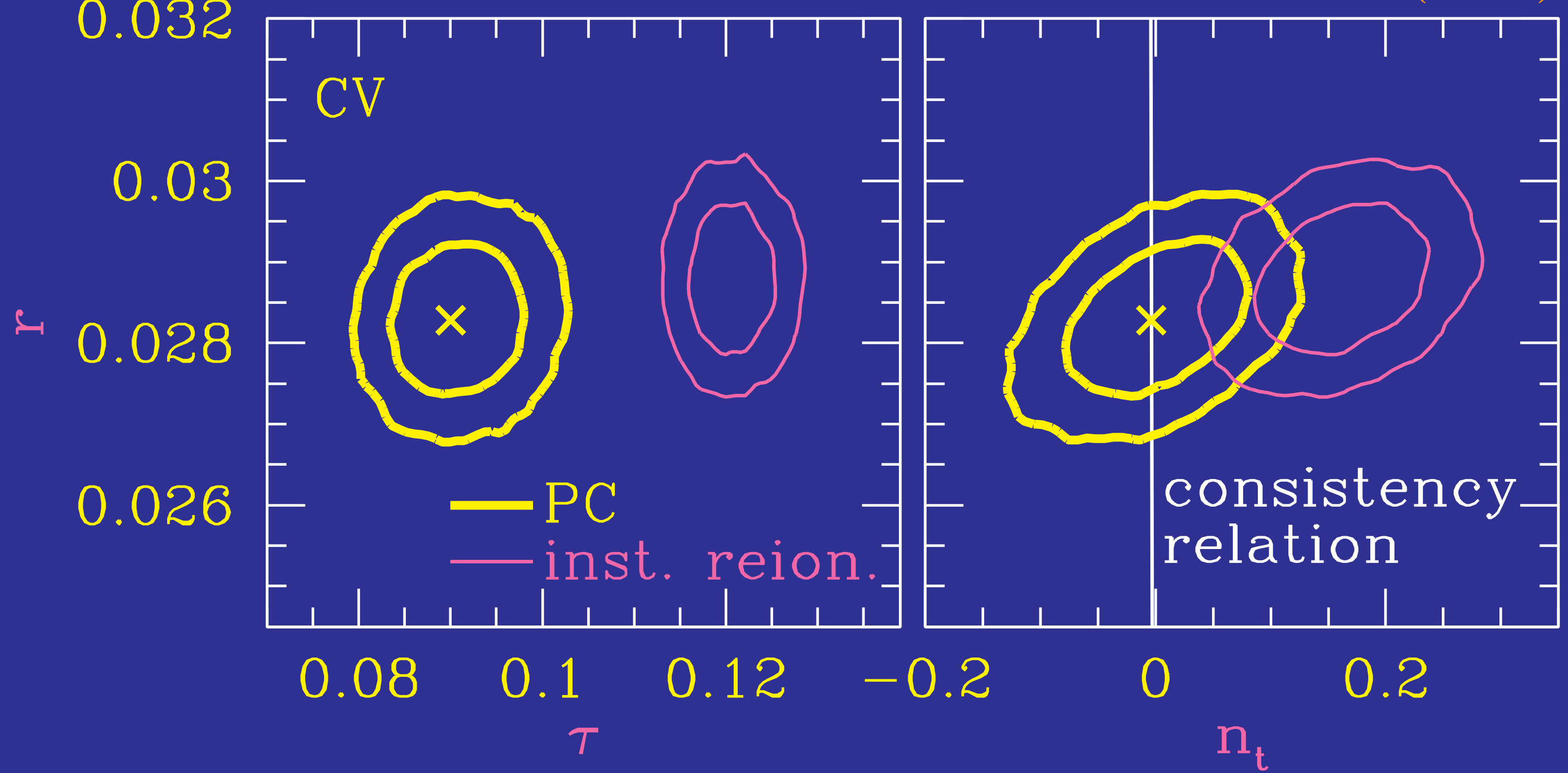
- Gravitational wave power proportional to energy scale to 4th power
- B-modes potentially observable for $V^{1/4} > 3 \times 10^{15}$ GeV with removal of lensing B-modes and foregrounds

- Measuring both the reionization bump and recombination peak tests slow roll consistency relation by constraining tensor tilt

Consistency Relation & Reionization

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

Mortonson & Hu (2007)



Summary

- CMB acoustic peaks provide precision measurements of
  - baryon density $\Omega_b h^2$
  - matter density $\Omega_m h^2$
  - distance to recombination D_*
  - amplitude and tilt of spectrum A_S, n_S

  and all should reach better than 1% precision with Planck
- CMB polarization provides windows on reionization, large scale anomalies, intervening matter and expansion history (through lensing)
- Inflationary origins will be tested further by precision spectrum, gravitational waves and non-Gaussianity
- Single-field slow roll inflation is highly falsifiable