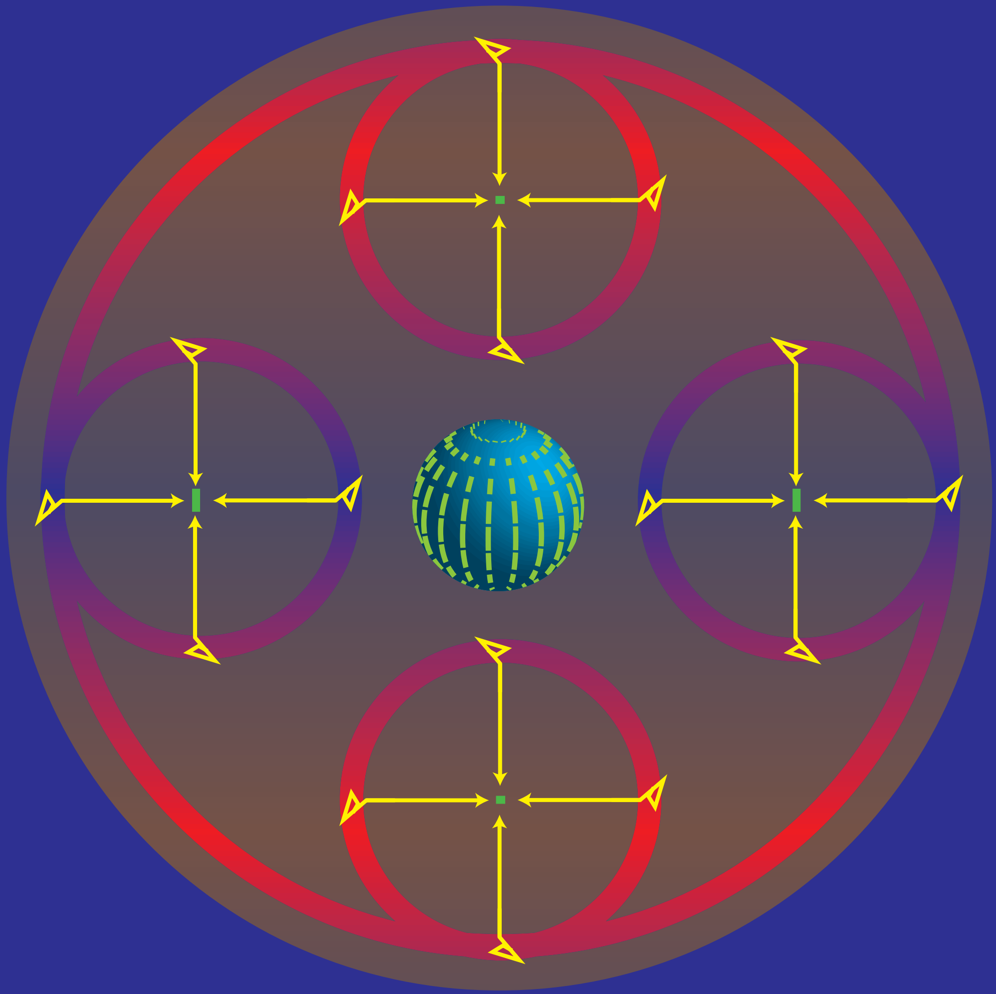
Secondary CMB Anisotropy



I: Reionization

Wayne Hu

Cabo, January 2009

Outline

Cabo Lectures

- Reionization
- B-modes

  Gravitational Lensing
- Cosmic Acceleration

Outline

Cabo Lectures

- Reionization
- B-modes

  Gravitational Lensing
- Cosmic Acceleration

Recent Reviews

- Primary and Secondary Anisotropy: Hu & Dodelson ARAA 40 171 (2002)
- Lensing: Lewis & Challinor Phys Rep. 429 1 (2006)
- Secondary Anisotropy: Aghanim, Majumdar, Silk Rep. Prog. Phys. 71 066902 (2008)
- Reionization: Zaldarriaga et al, CMBpol White Paper (2008)

Outline

Cabo Lectures (not all inclusive!)

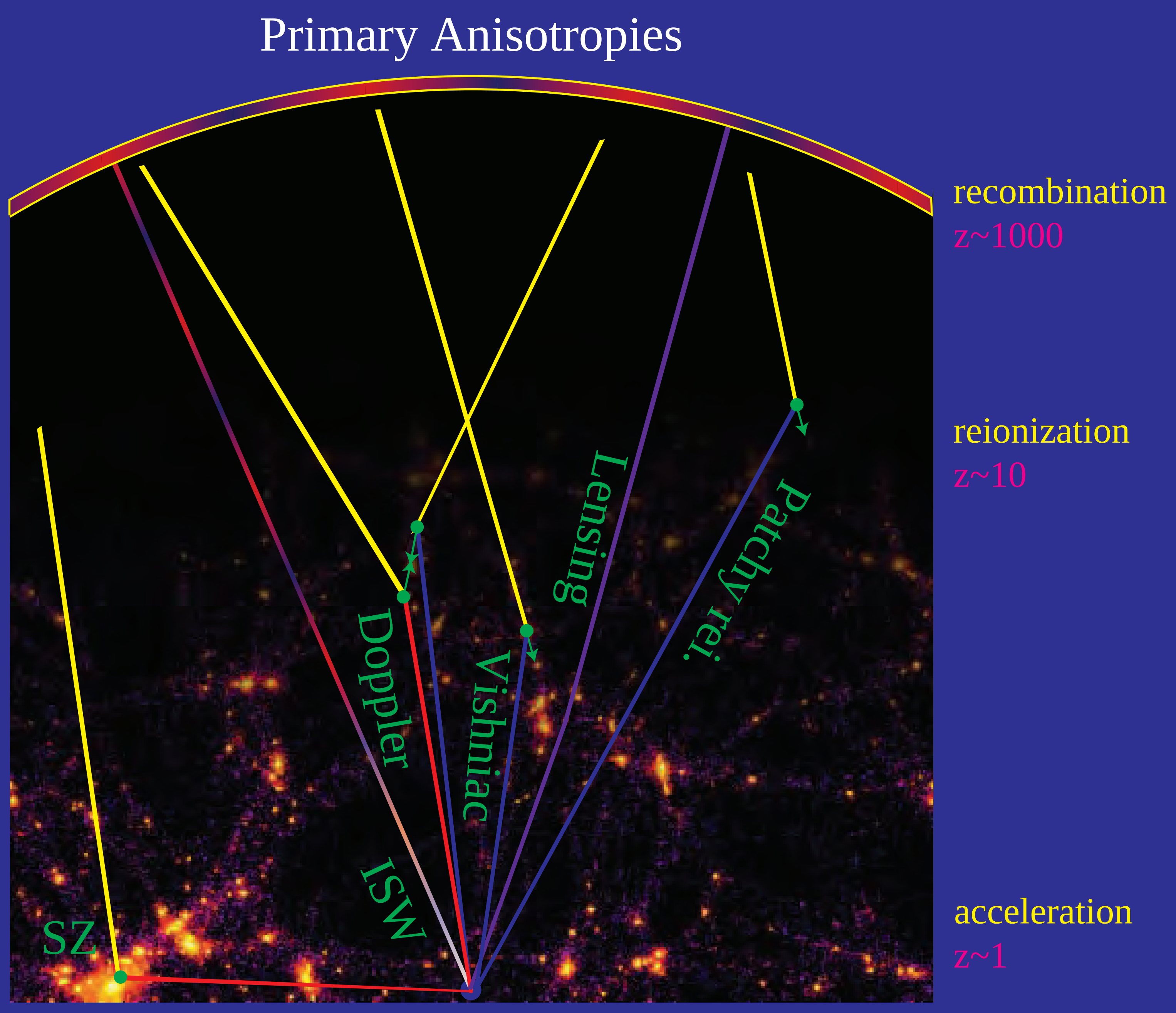
- Reionization
- B-modes

  Gravitational Lensing
- Cosmic Acceleration

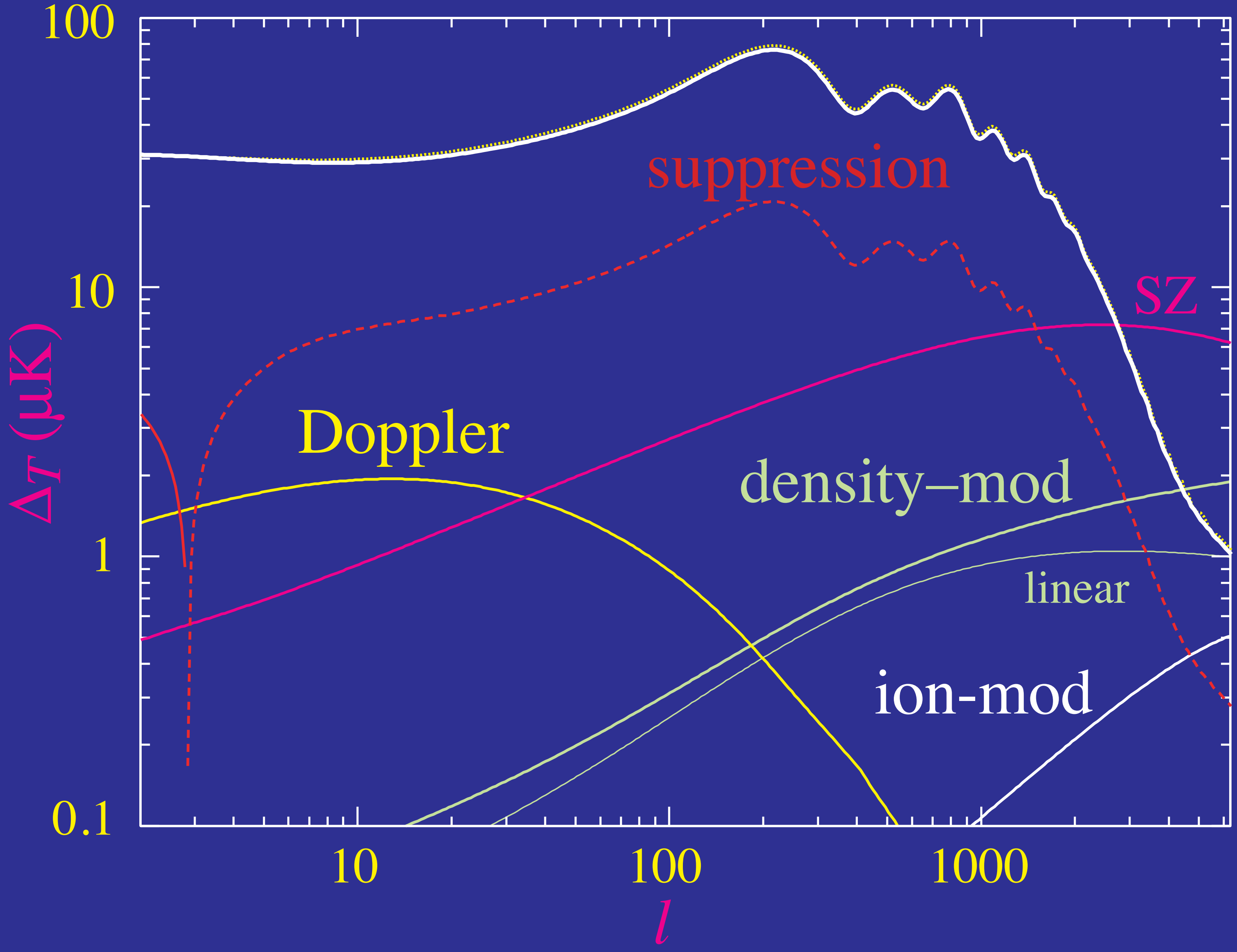
Recent Reviews

- Primary and Secondary Anisotropy: Hu & Dodelson ARAA 40 171 (2002)
- Lensing: Lewis & Challinor Phys Rep. 429 1 (2006)
- Secondary Anisotropy: Aghanim, Majumdar, Silk Rep. Prog. Phys. 71 066902 (2008)
- Reionization: Zaldarriaga et al, CMBpol White Paper (2008)

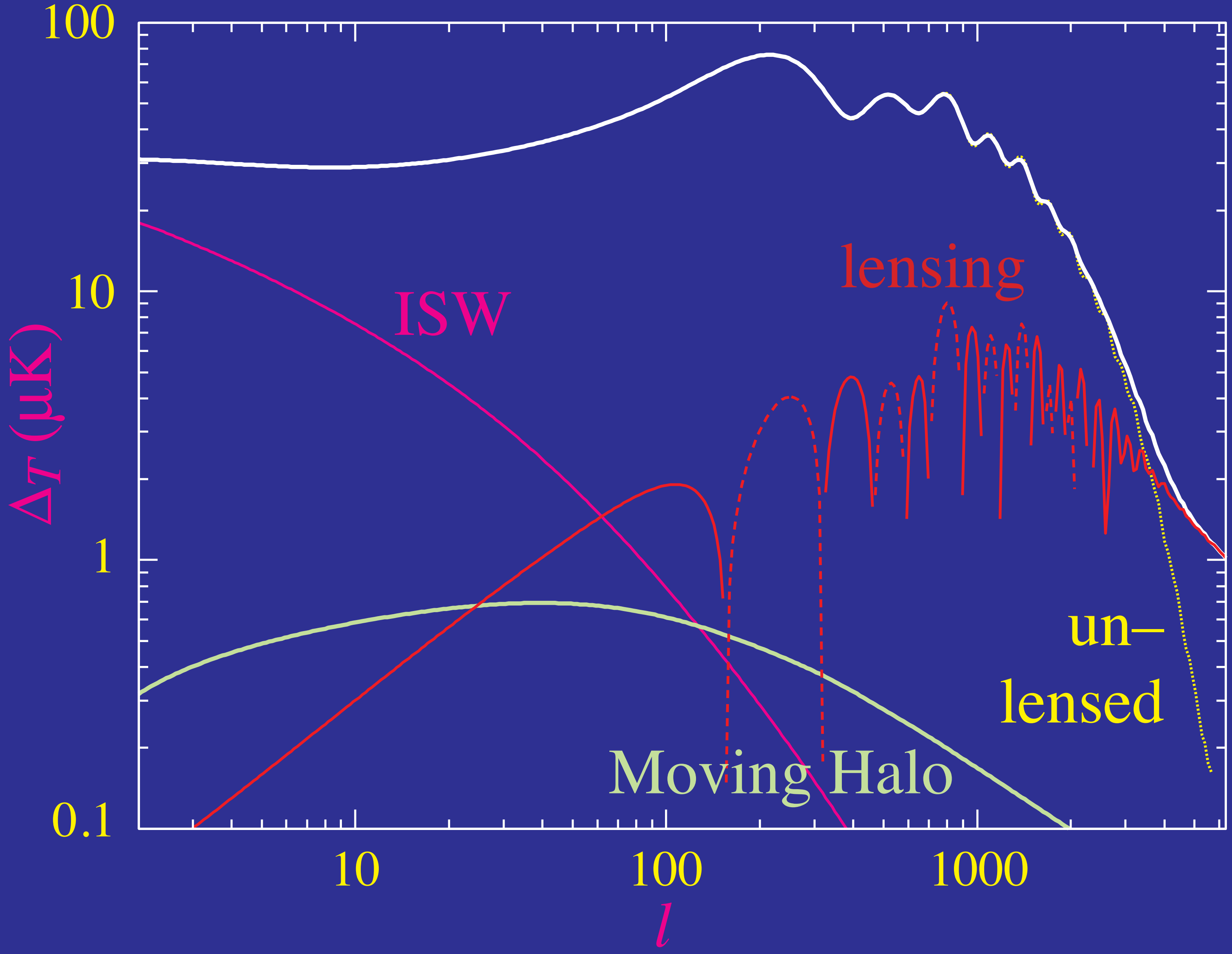
Physics of Secondary Anisotropies



Scattering Secondaries

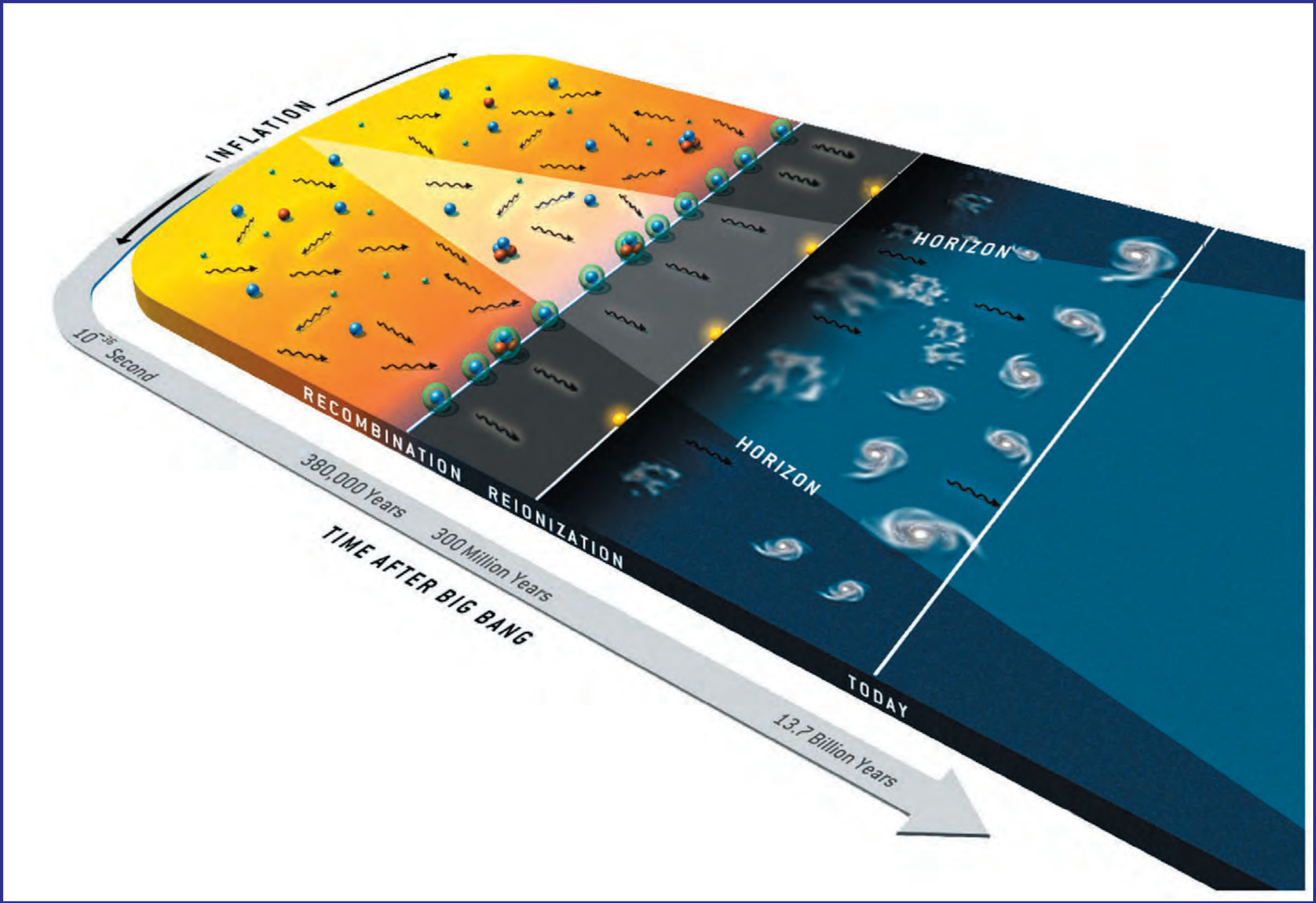


Gravitational Secondaries



Reionization

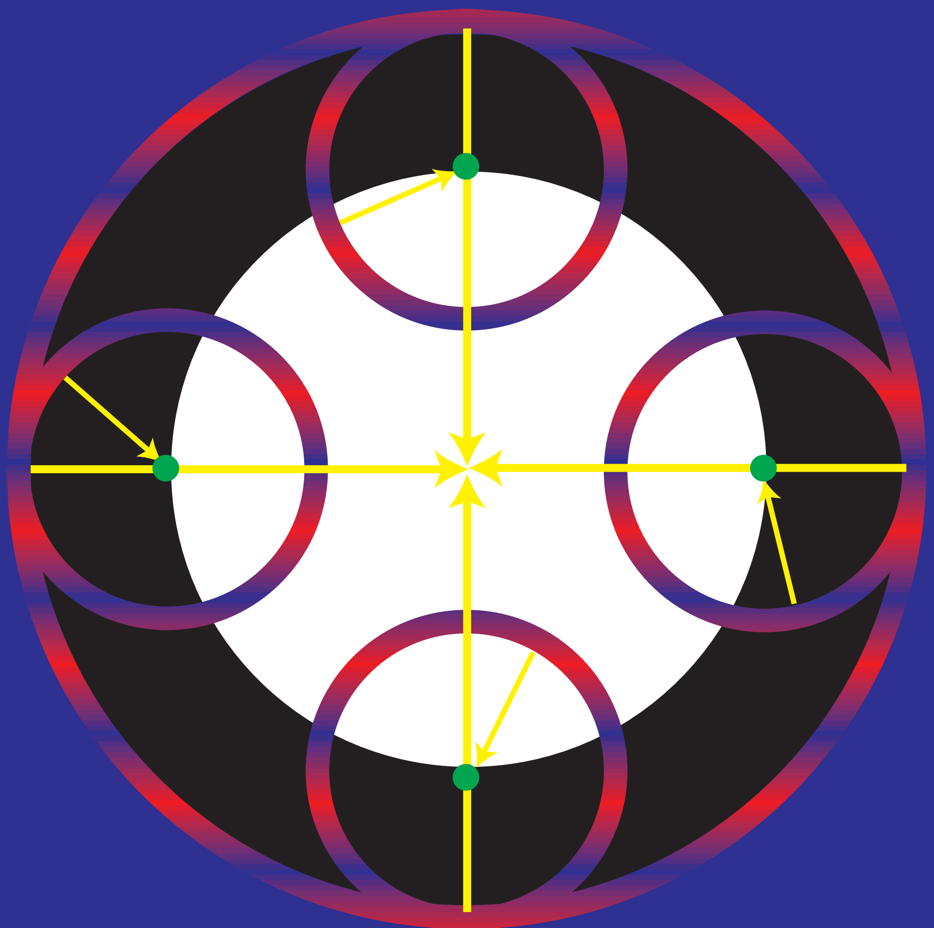
Across the Horizon



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

Anisotropy Suppression

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



Why Are Secondaries So Smalll?

- Original anisotropy replaced by new secondary sources
- Late universe more developed than early universe

  Density fluctuations nonlinear not 10^{-5}

  Velocity field 10^{-3} not not 10^{-5}
- Shouldn't $\Delta T/T \sim \tau v \sim 10^{-4}$?
- Limber says no!
- Spatial and angular dependence of sources contributing and cancelling broadly in redshift

Integral Solution

- Formal solution to the radiative transfer or Boltzmann equation involves integrating sources across line of sight
- Linear solution describes the decomposition of the source $S_\ell^{(m)}$ with its local angular dependence and plane wave spatial dependence as seen at a distance $\mathbf{x} = D\hat{\mathbf{n}}$.
- Proceed by decomposing the angular dependence of the plane wave

$$e^{i\mathbf{k}\cdot\mathbf{x}} = \sum_\ell (-i)^\ell \sqrt{4\pi(2\ell+1)} j_\ell(kD) Y_\ell^0(\hat{\mathbf{n}})$$

- Recouple to the local angular dependence of G_ℓ^m

$$G_{\ell_s}^m = \sum_\ell (-i)^\ell \sqrt{4\pi(2\ell+1)} \alpha_{\ell_s \ell}^{(m)}(kD) Y_\ell^m(\hat{\mathbf{n}})$$

Integral Solution

- Projection kernels (monopole, temperature; dipole, doppler):

$$\ell_s = 0, \quad m = 0 \qquad\qquad \alpha_{0\ell}^{(0)} \equiv j_\ell$$

$$\ell_s = 1, \quad m = 0 \qquad\qquad \alpha_{1\ell}^{(0)} \equiv j'_\ell$$

- Integral solution: for $\Theta = \Delta T/T$

$$\frac{\Theta_\ell^{(m)}(k,0)}{2\ell+1} = \int_0^\infty dD e^{-\tau} \sum_{\ell_s} S_{\ell_s}^{(m)} \alpha_{\ell_s \ell}^{(m)}(kD)$$

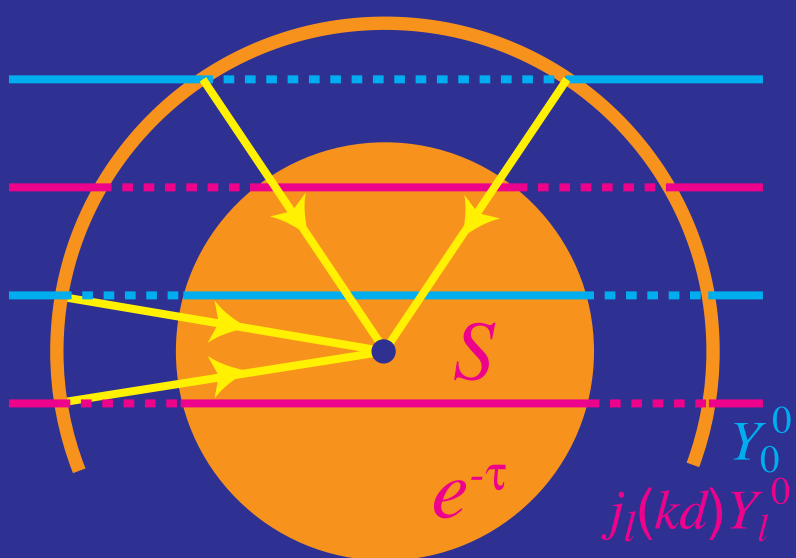
- Power spectrum:

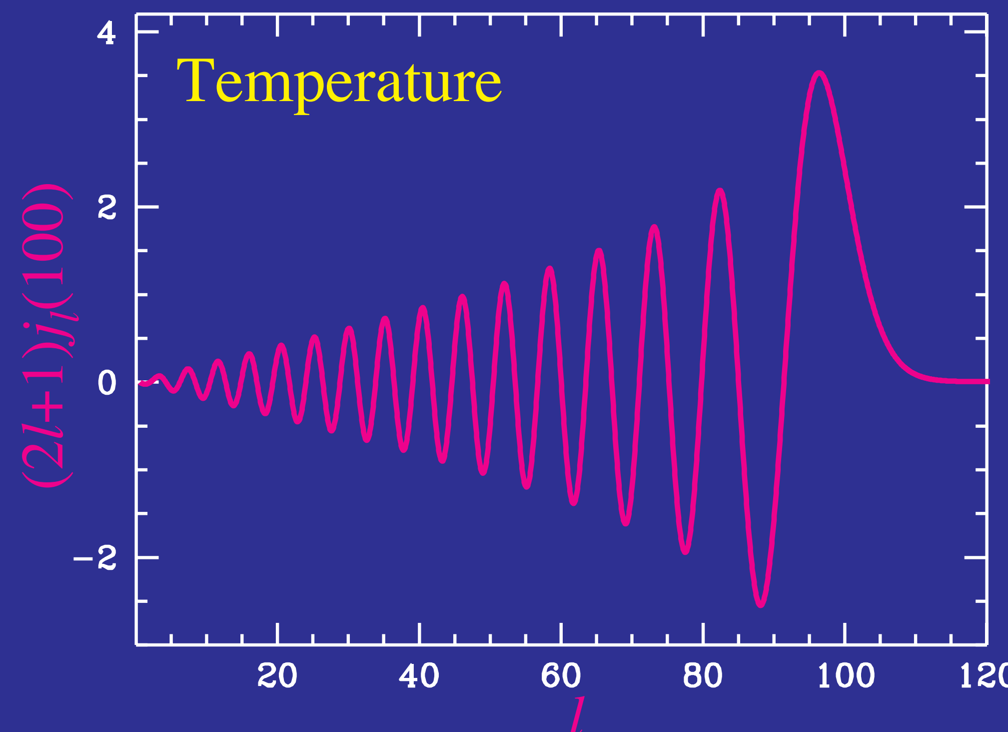
$$C_\ell = \frac{2}{\pi} \int \frac{dk}{k} \sum_m \frac{k^3 \langle \Theta_\ell^{(m)*} \Theta_\ell^{(m)} \rangle}{(2\ell+1)^2}$$

- Solving for C_ℓ reduces to solving for the behavior of a handful of sources. Straightforward generalization to polarization.

Anisotropy Suppression and Regeneration

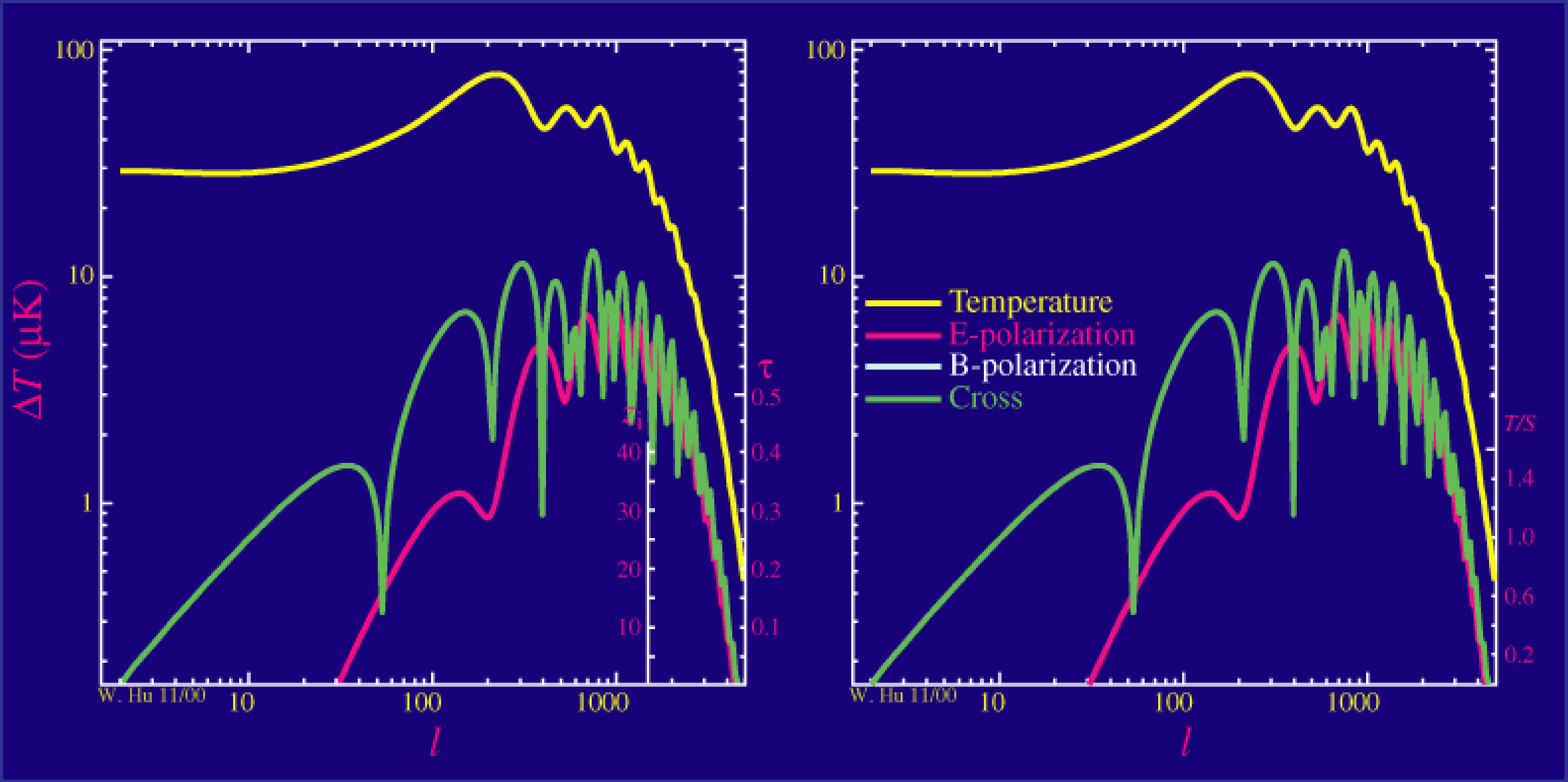
- Recombination sources obscured and replaced with secondary sources that suffer Limber cancellation from integrating over many wavelengths of the source
- Net suppression despite substantially larger sources due to growth of structure except beyond damping tail <10’





Reionization Suppression

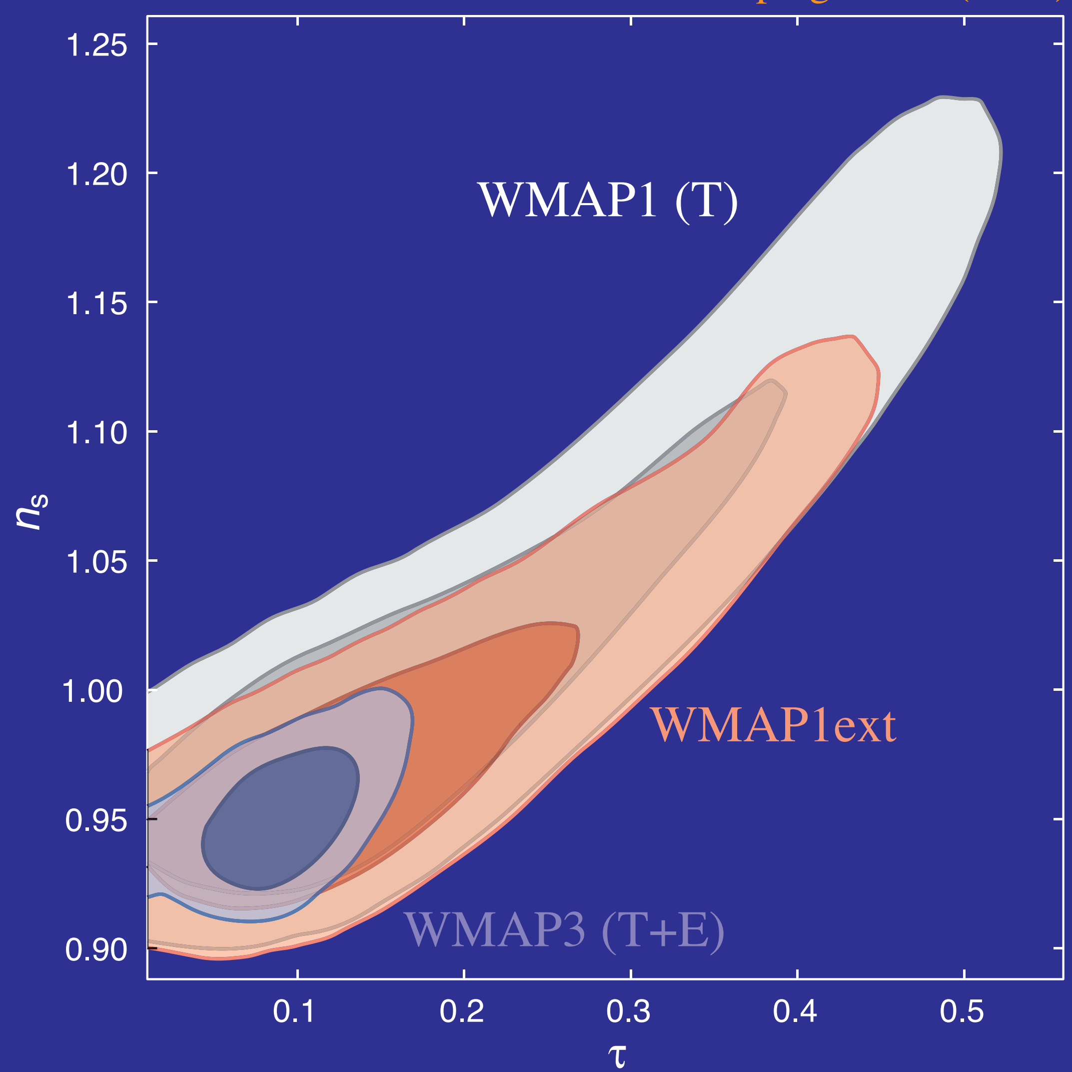
- Rescattering suppresses primary temperature and polarization anisotropy according to optical depth, fraction of photons rescattered



Tilt-τ Degeneracy

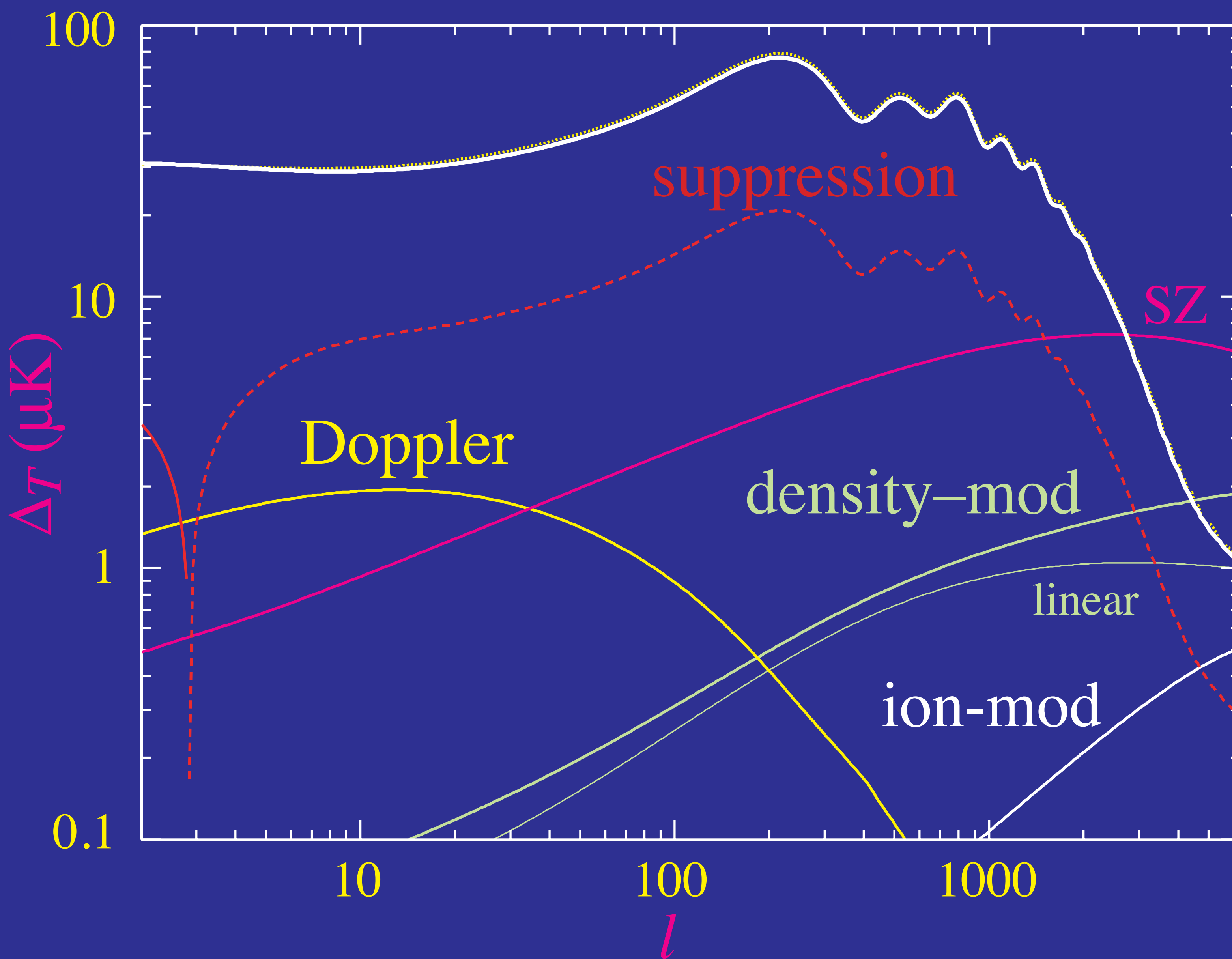
- Only anisotropy at reionization (high k), not isotropic temperature fluctuations (low k) - is suppressed leading to effective tilt for WMAP (not Planck)

Spergel et al (2006)



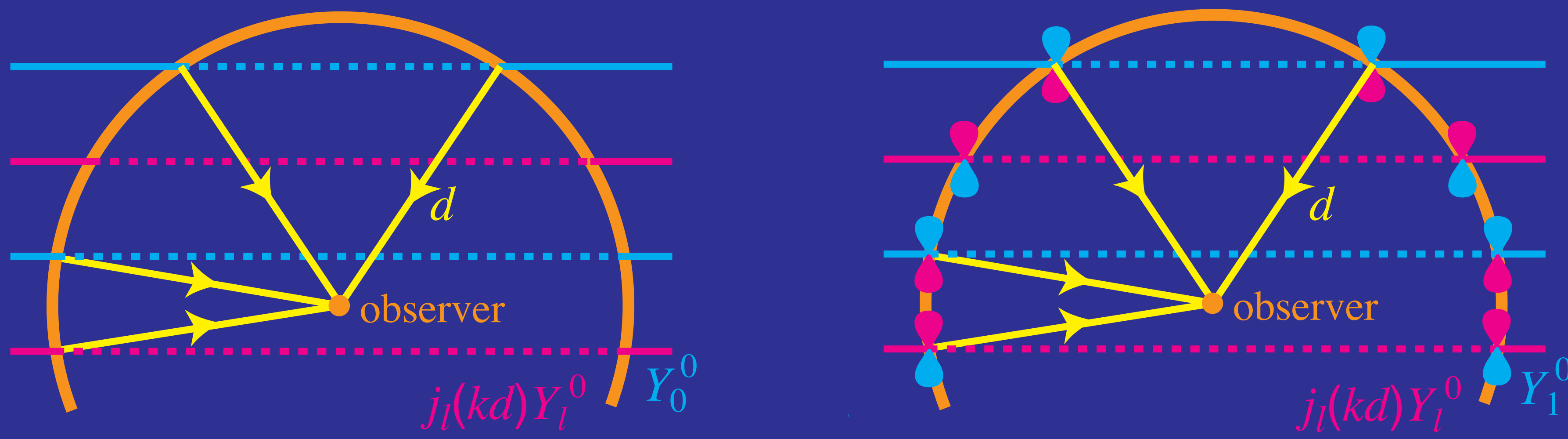
Doppler Effect

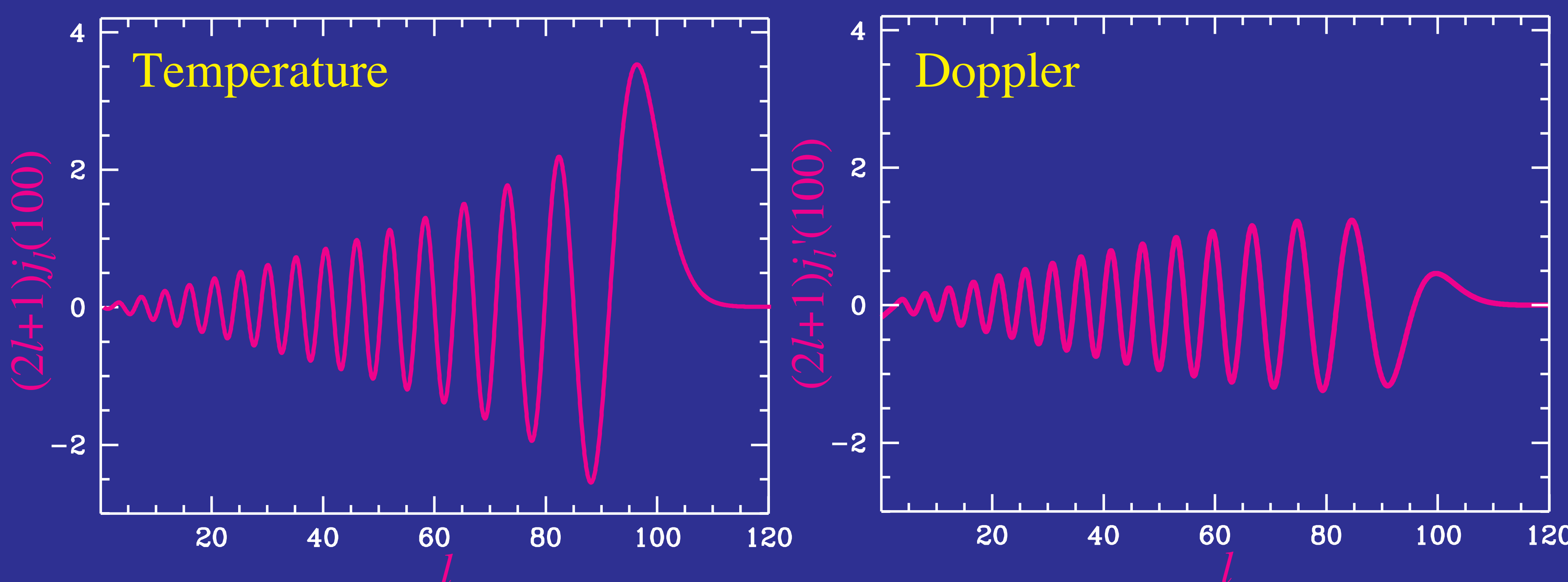
Scattering Secondaries



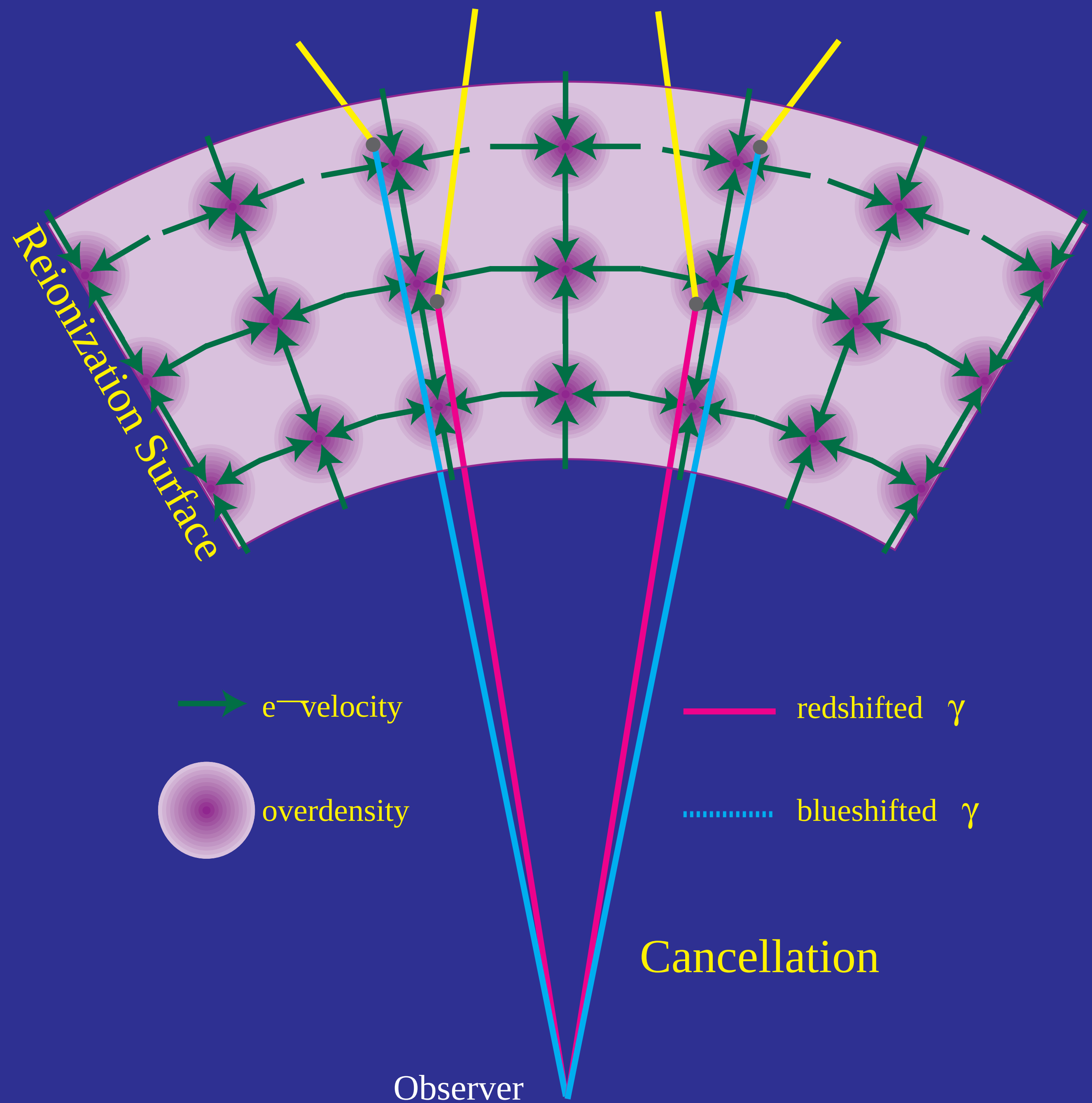
Doppler Effect in Limber Approximation

- Only fluctuations transverse to line of sight survive in Limber approx but linear Doppler effect has no contribution in this direction

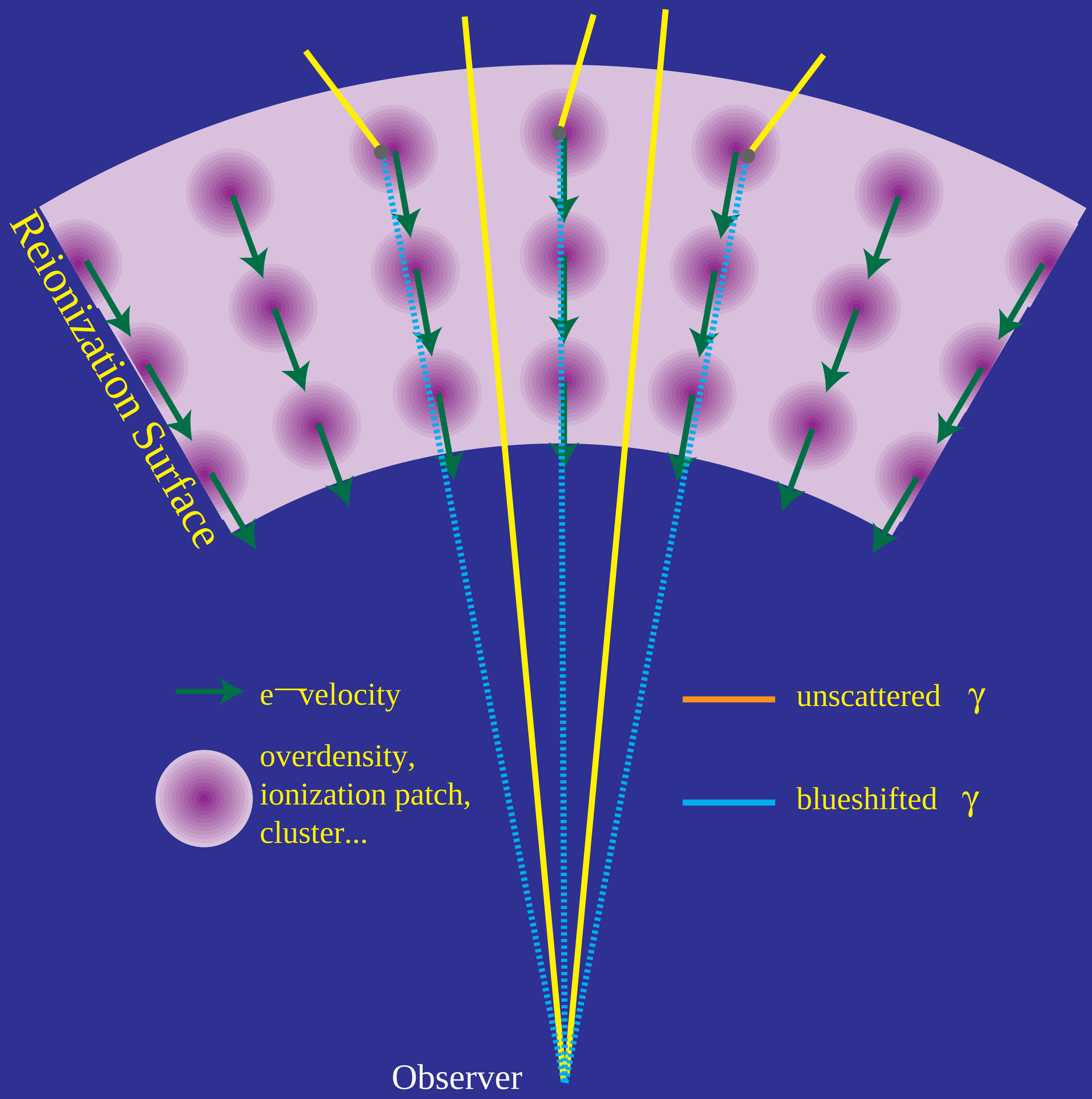




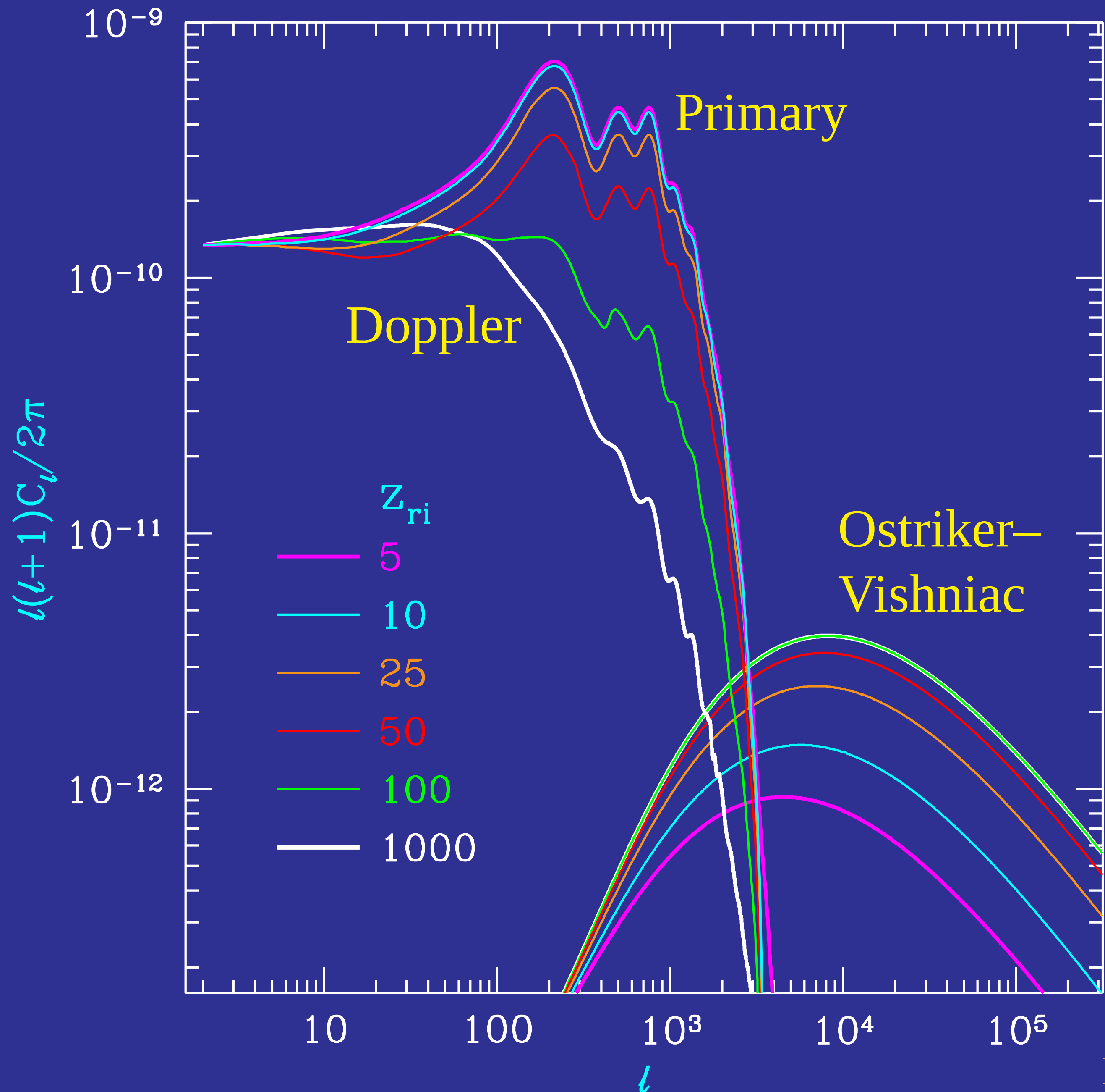
Cancellation of the Linear Effect



Modulated Doppler Effect



Ostriker–Vishniac Effect

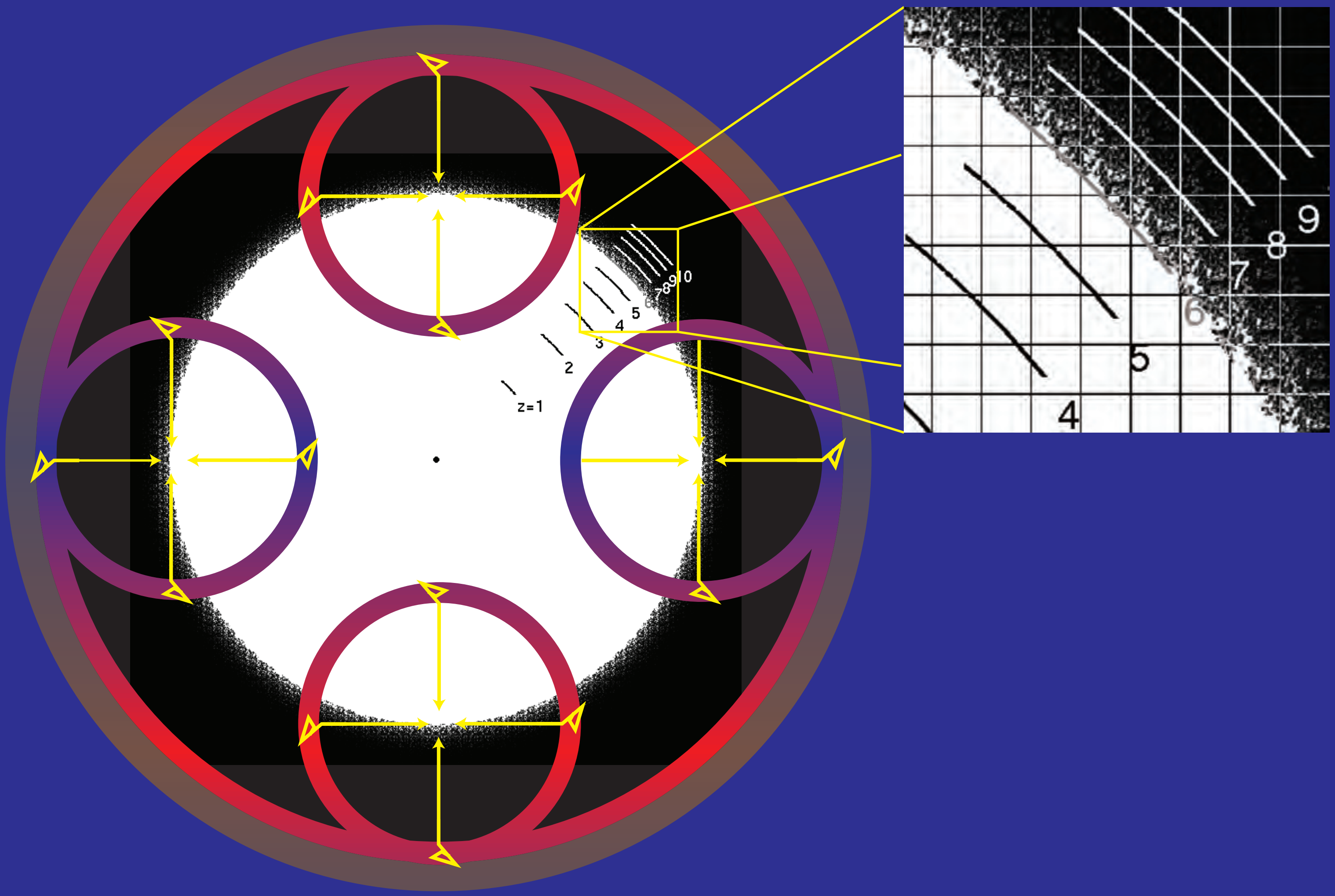


see Shirley Ho's talk

Hu & White (1996)

Inhomogeneous Ionization

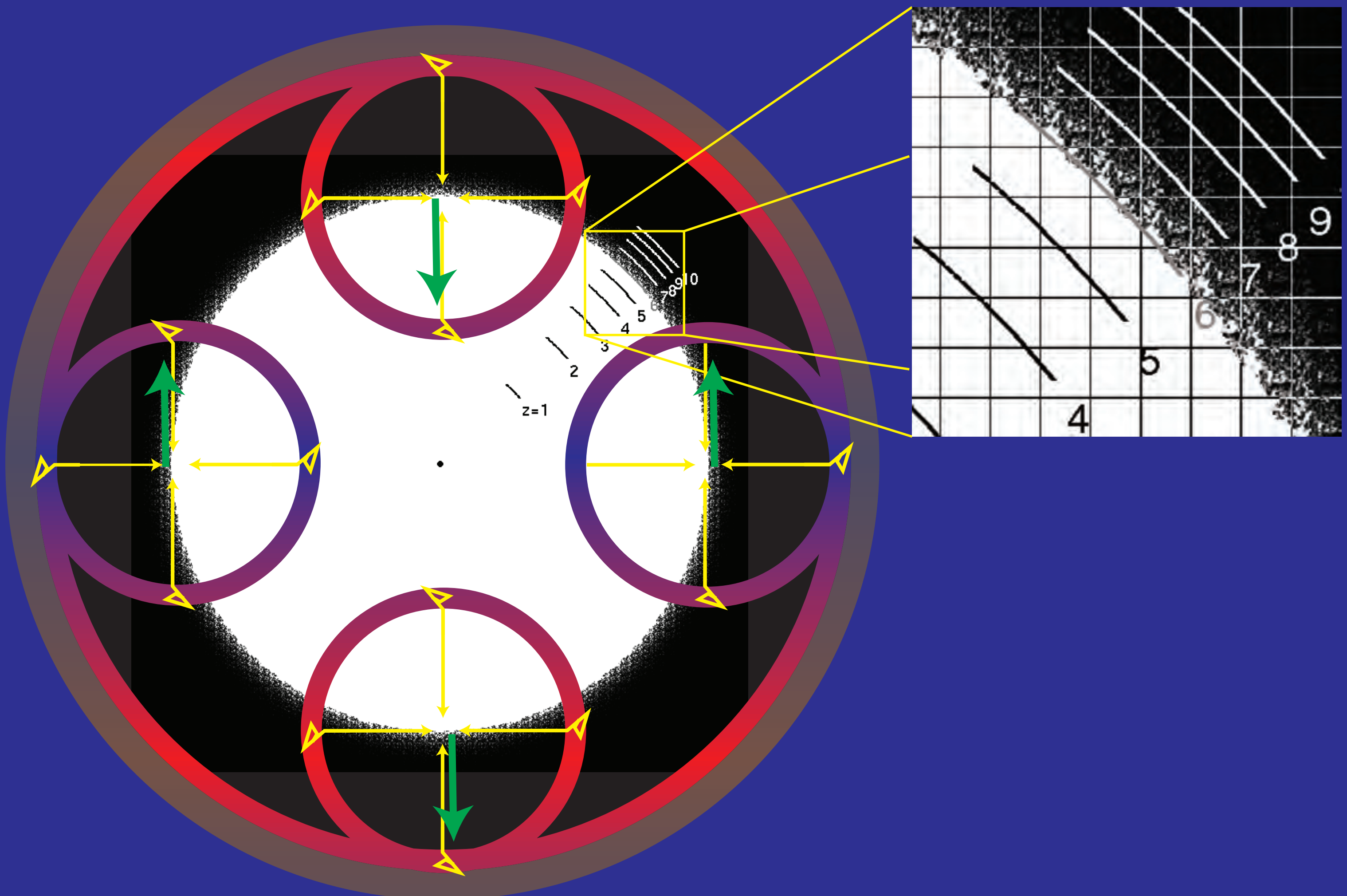
- As reionization completes, ionization regions grow and fill the space



Zahn et al. (2006) [Mortonson et al (2009)]

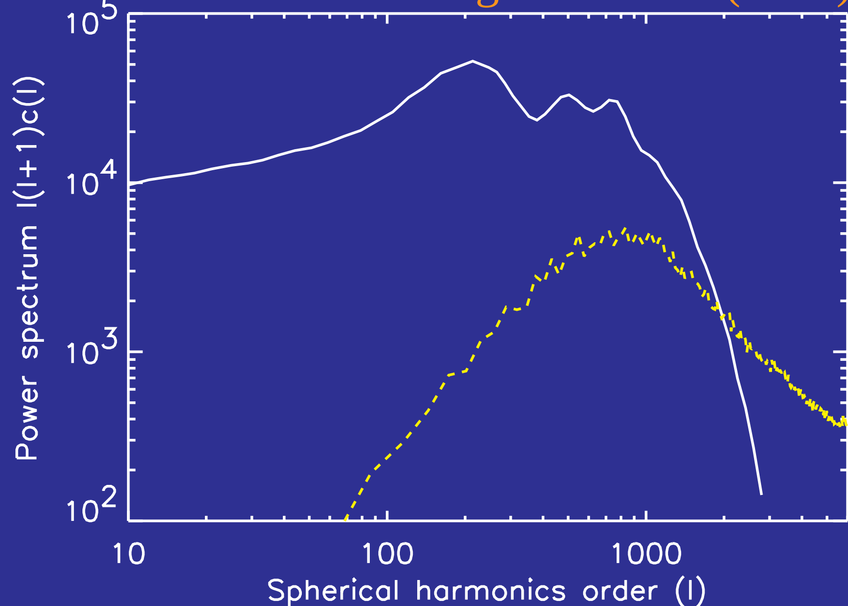
Inhomogeneous Ionization

- Provides a source for modulated Doppler effect that appears on the scale of the ionization region



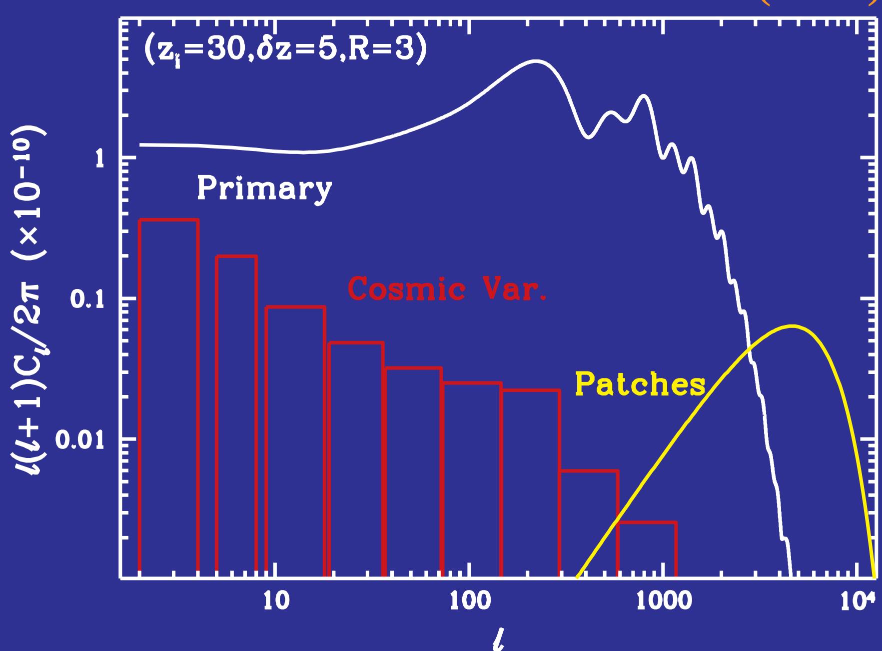
Patchy Reionization

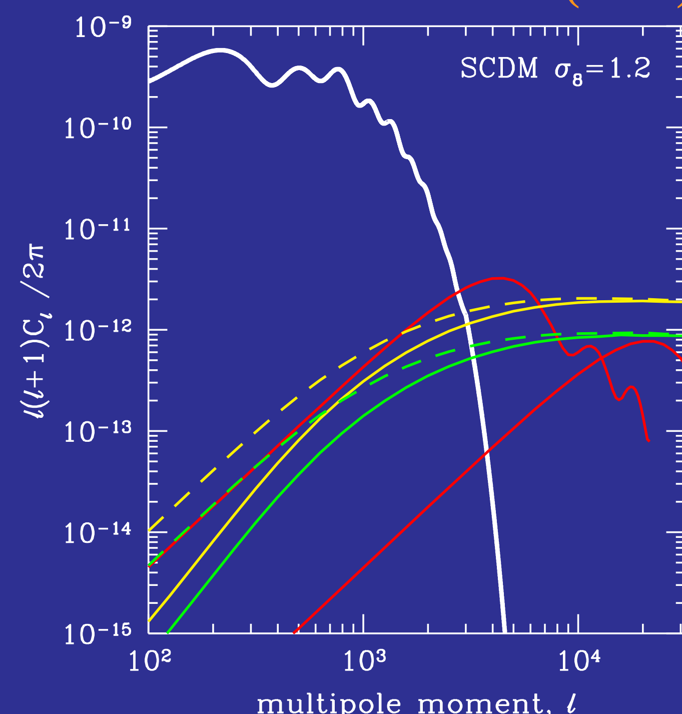
Aghanim et al (1996)



Knox, Scocciomarro & Dodelson (1998)

Gruzinov & Hu (1998)

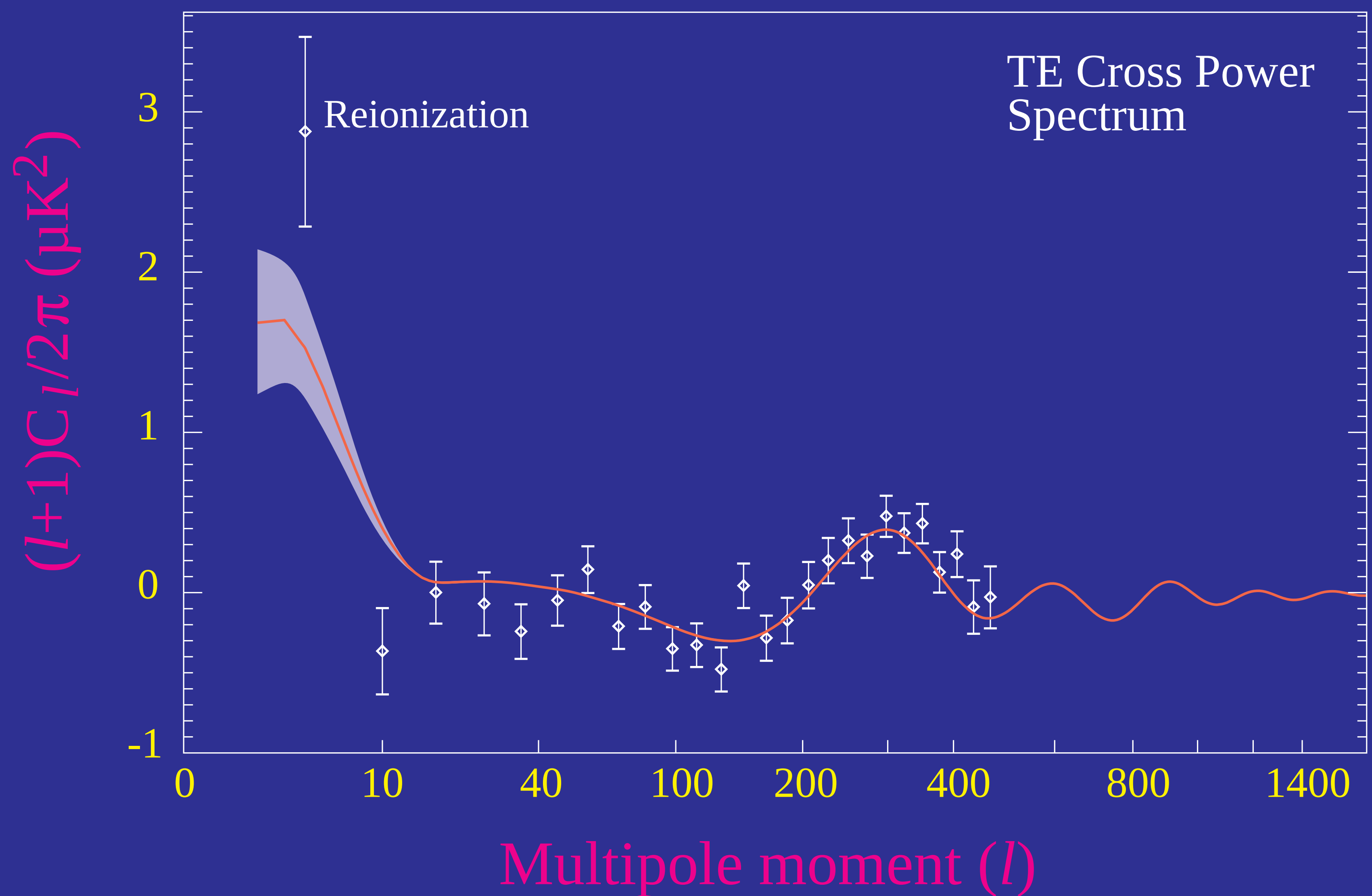




Secondary Polarization

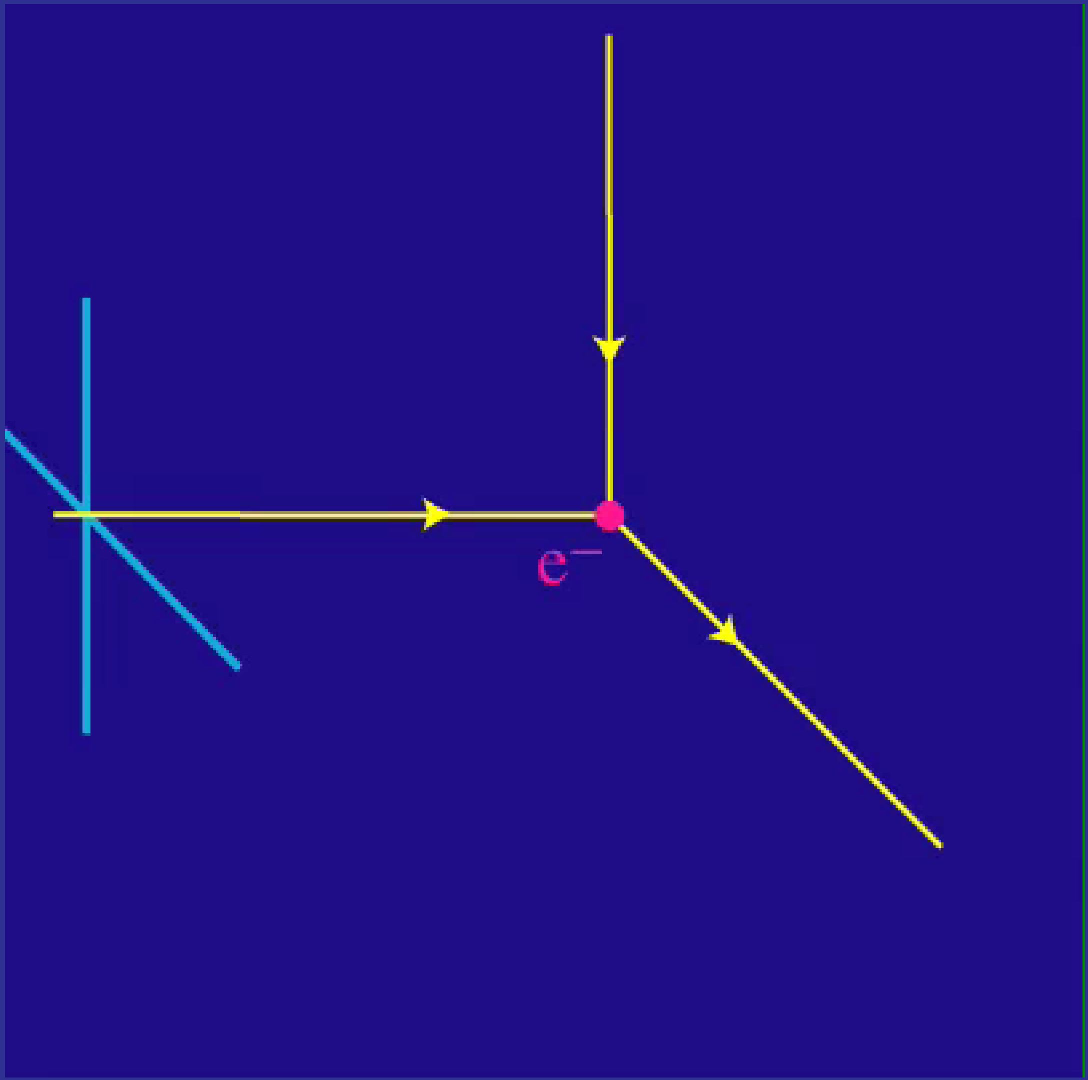
WMAP Correlation

- Reionization polarization first detected in WMAP1 through temperature cross correlation at an anomalously high value



Polarization from Thomson Scattering

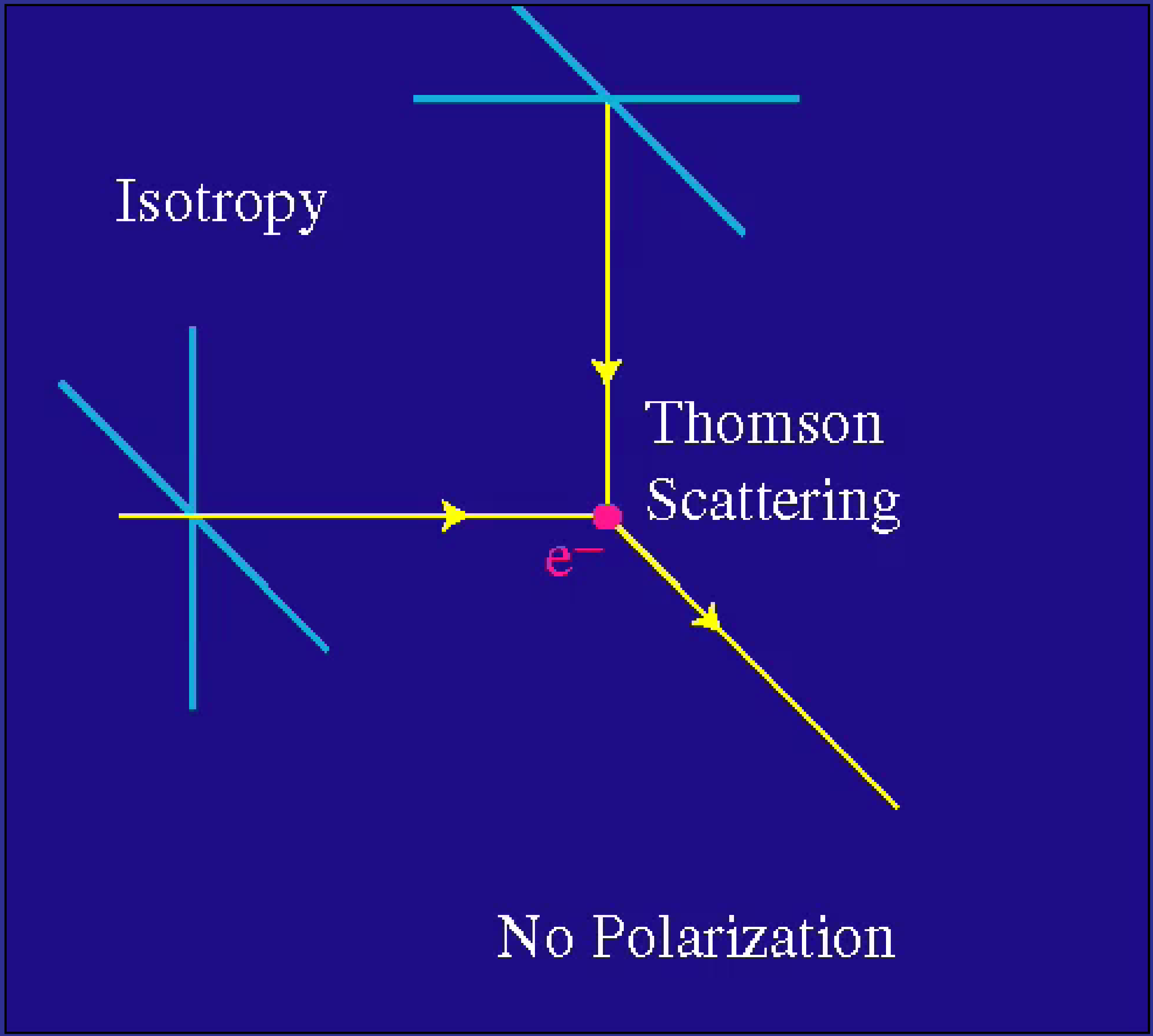
- Differential cross section depends on polarization and angle



$$\frac{d\sigma}{d\Omega} = \frac{3}{8\pi}|\hat{\varepsilon}' \cdot \hat{\varepsilon}|^2 \sigma_T$$

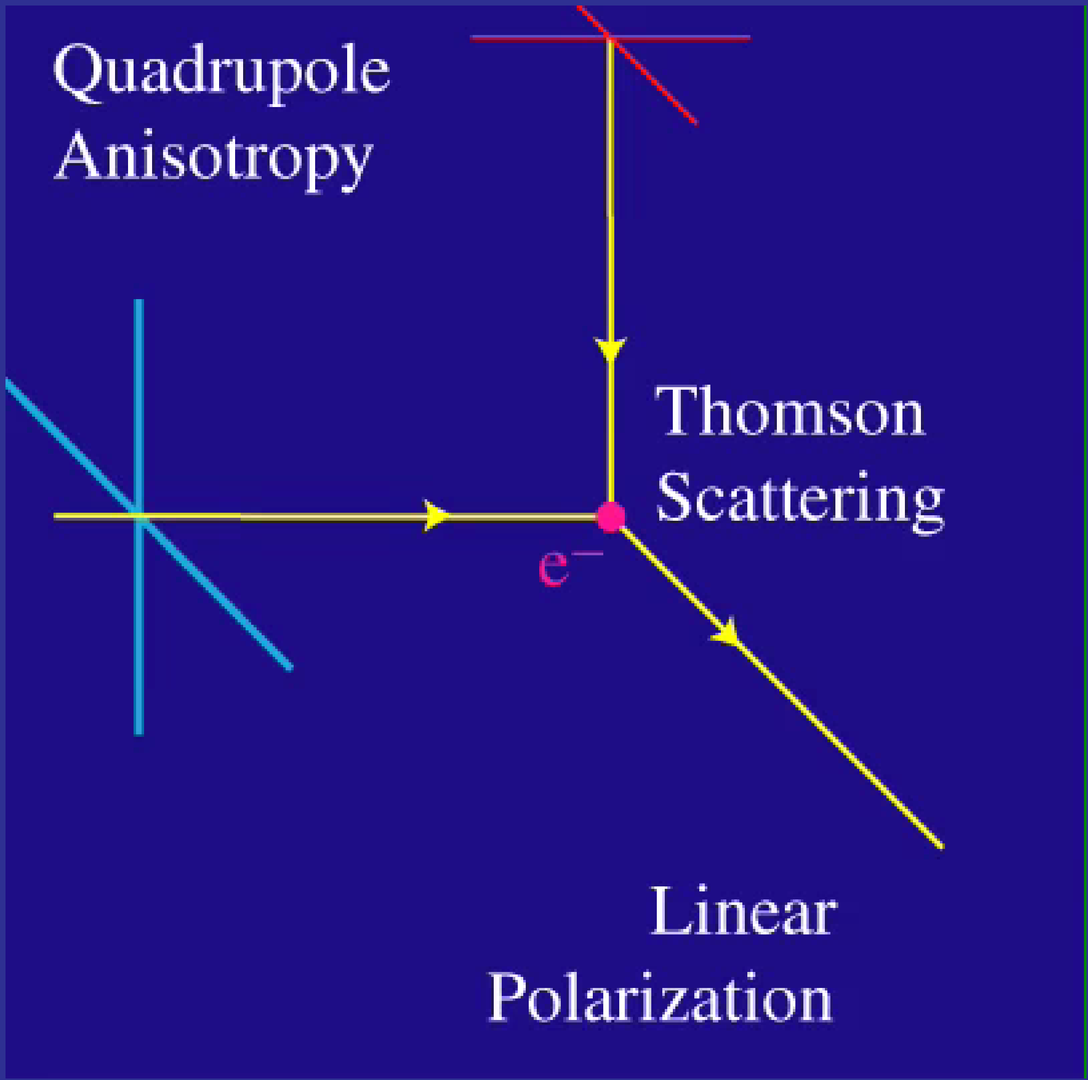
Polarization from Thomson Scattering

- Isotropic radiation scatters into unpolarized radiation



Polarization from Thomson Scattering

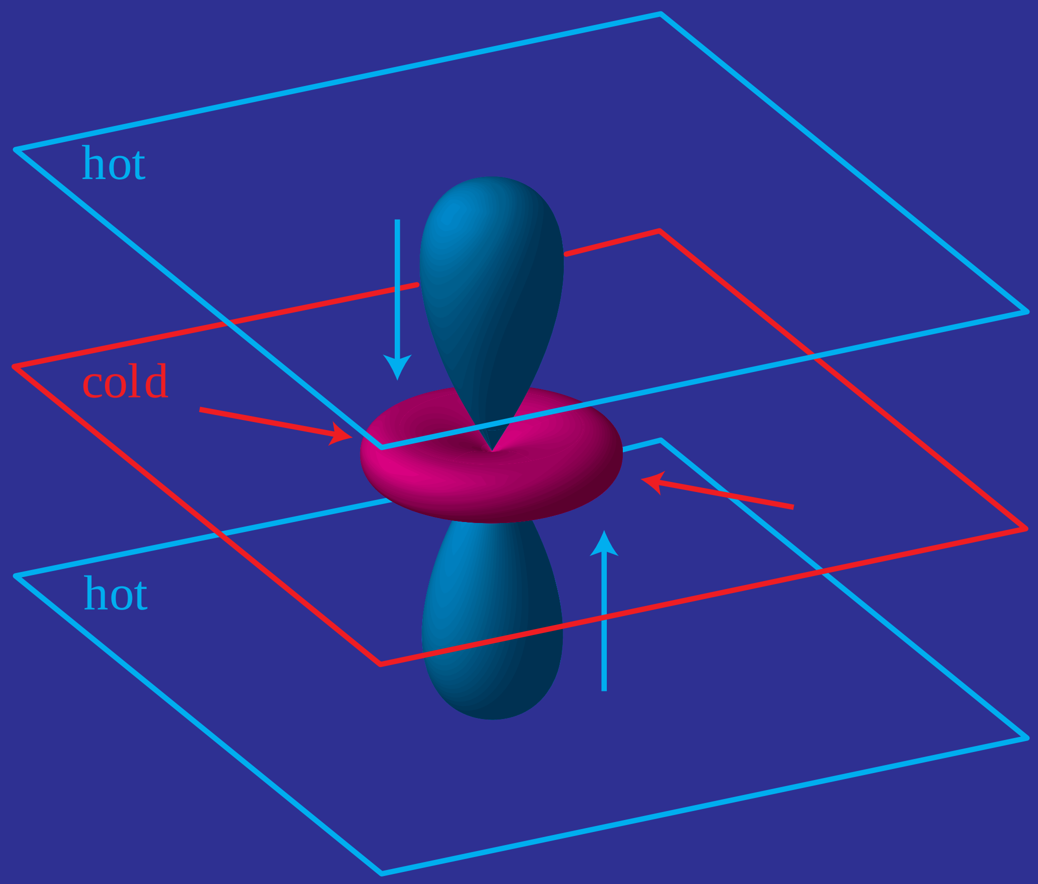
- Quadrupole anisotropies scatter into linear polarization



aligned with
cold lobe

Whence Quadrupoles?

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

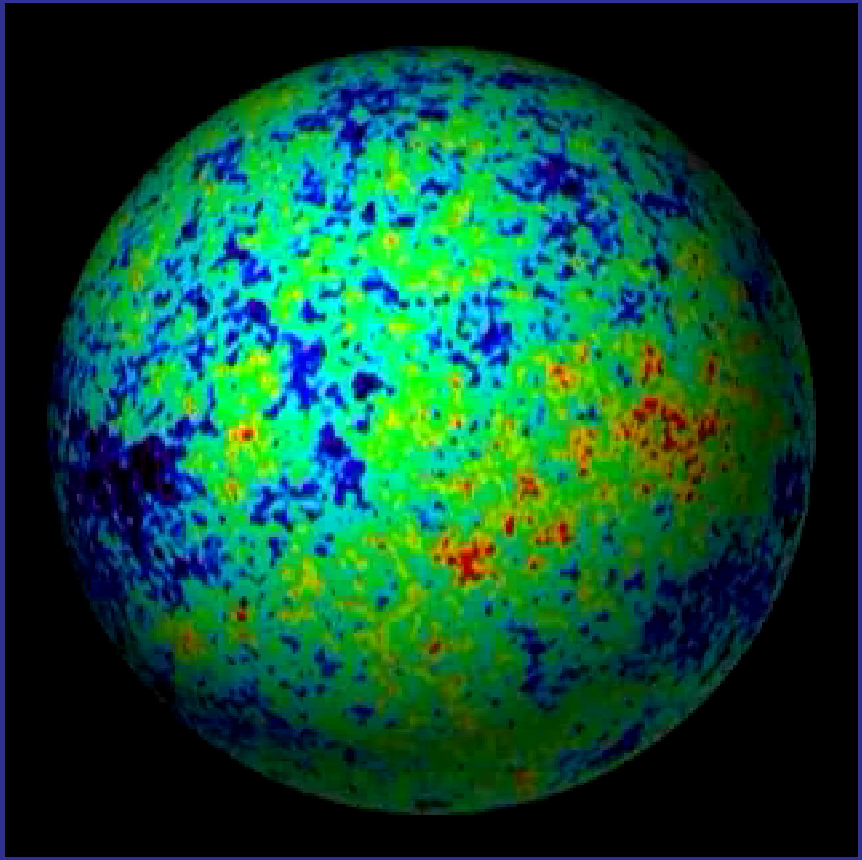


(Scalar) Temperature Inhomogeneity

Hu & White (1997)

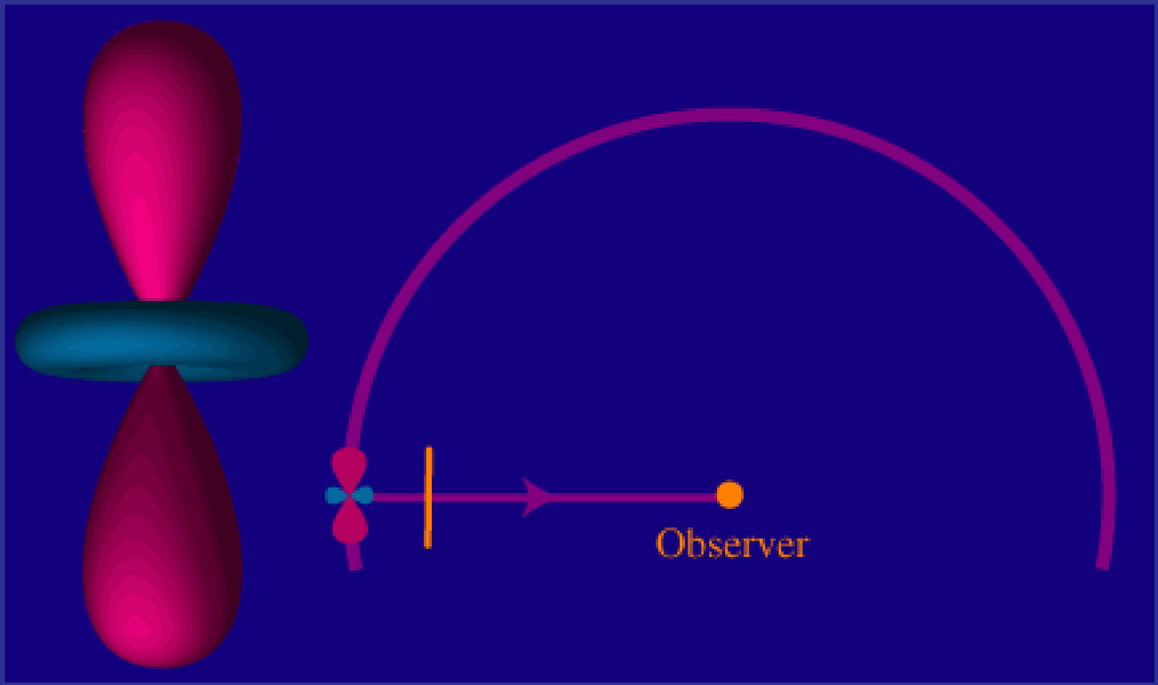
CMB Anisotropy

- WMAP map of the CMB temperature anisotropy



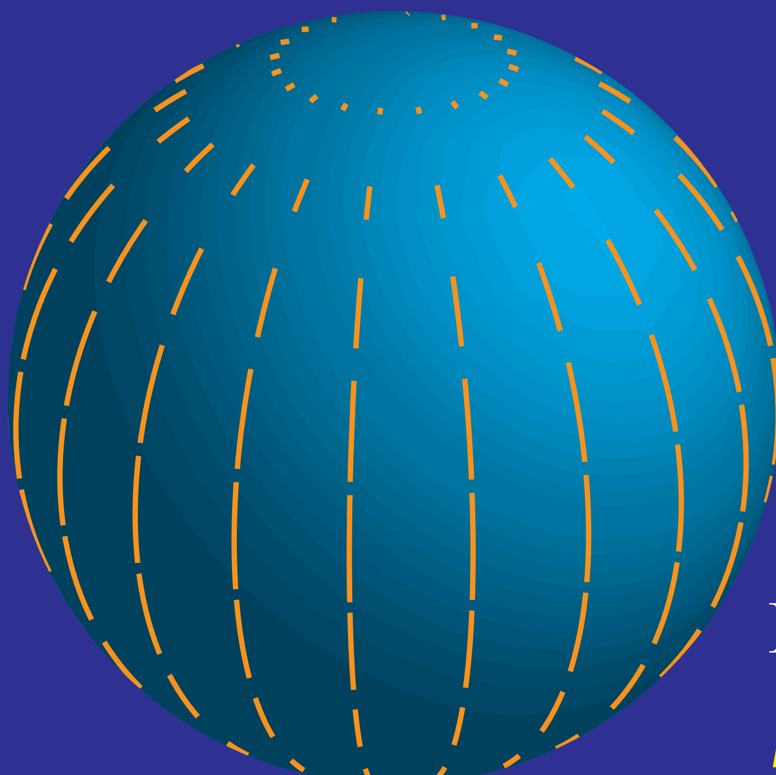
Whence Polarization Anisotropy?

- Observed photons scatter into the line of sight
- Polarization arises from the projection of the quadrupole on the transverse plane



Polarization Multipoles

- Mathematically pattern is described by the tensor (spin-2) spherical harmonics [eigenfunctions of Laplacian on trace-free 2 tensor]
- Correspondence with scalar spherical harmonics established via Clebsch-Gordan coefficients (spin x orbital)
- Amplitude of the coefficients in the spherical harmonic expansion are the multipole moments; averaged square is the power

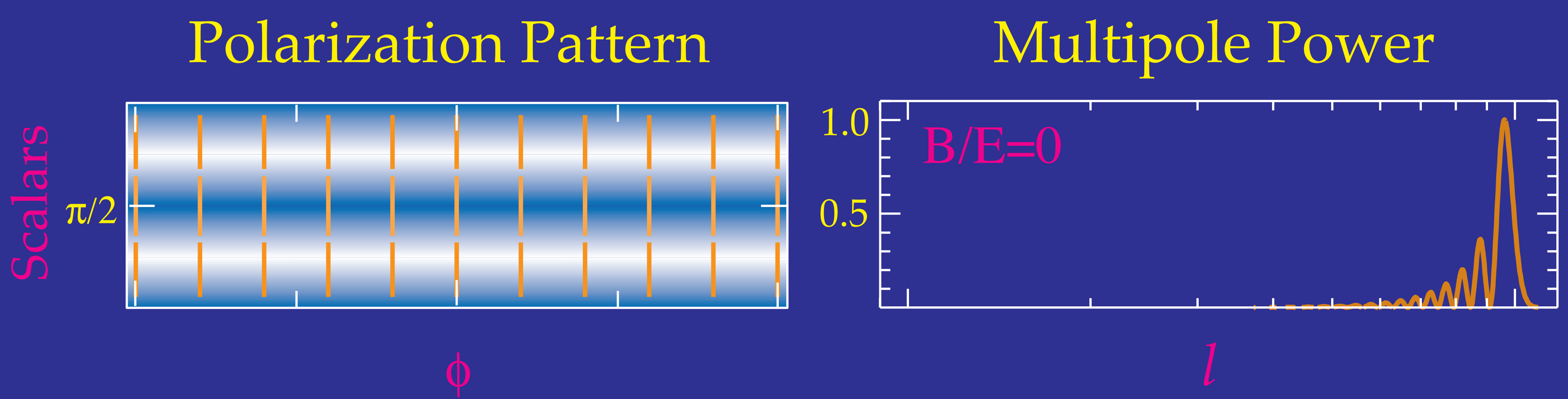


E-tensor harmonic

$l=2,\ m=0$

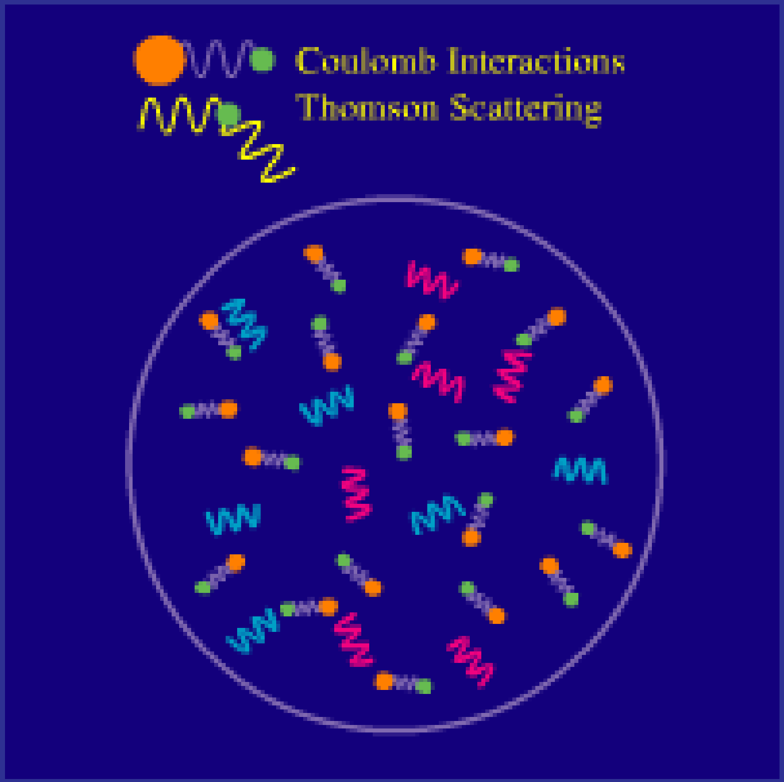
Modulation by Plane Wave

- Amplitude modulated by plane wave → higher multipole moments
- Direction detemined by perturbation type → E-modes

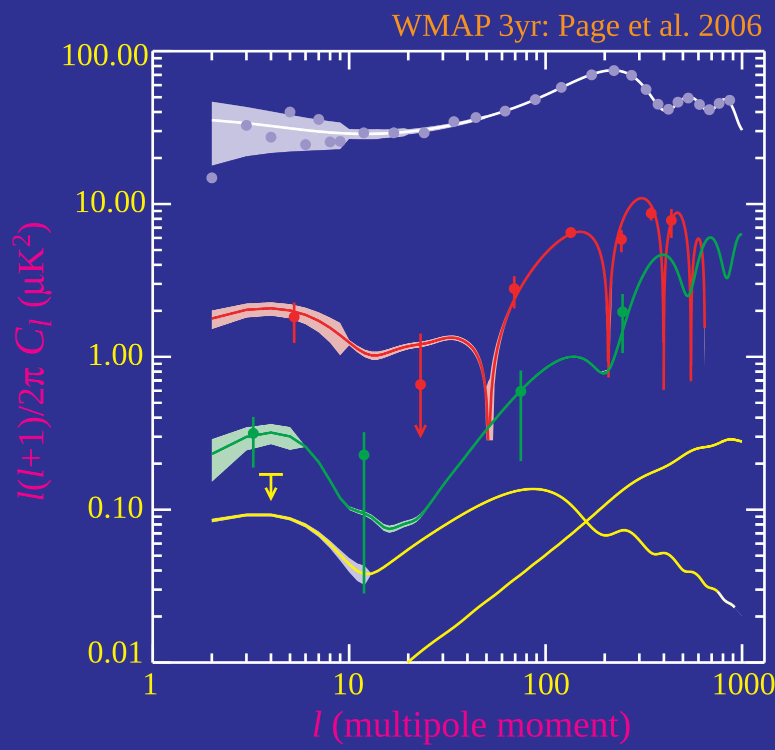


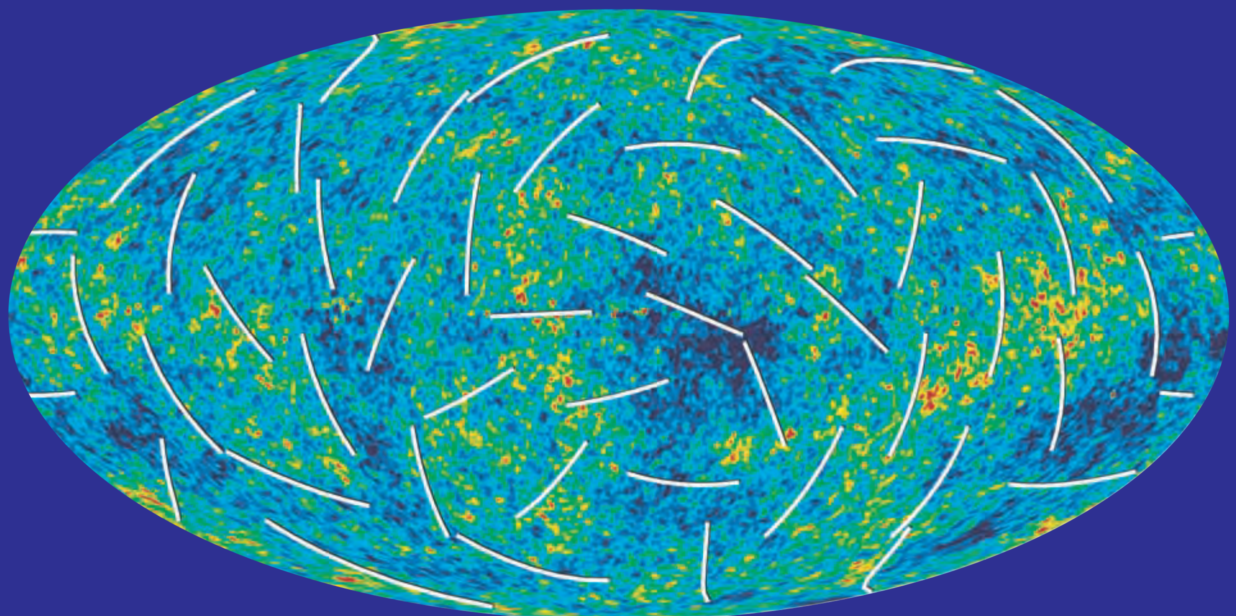
A Catch-22

- Polarization is generated by scattering of anisotropic radiation
- Scattering isotropizes radiation
- Polarization only arises in optically thin conditions: reionization and end of recombination
- Polarization fraction is at best a small fraction of the 10^{-5} anisotropy: $\sim 10^{-6}$ or μK in amplitude



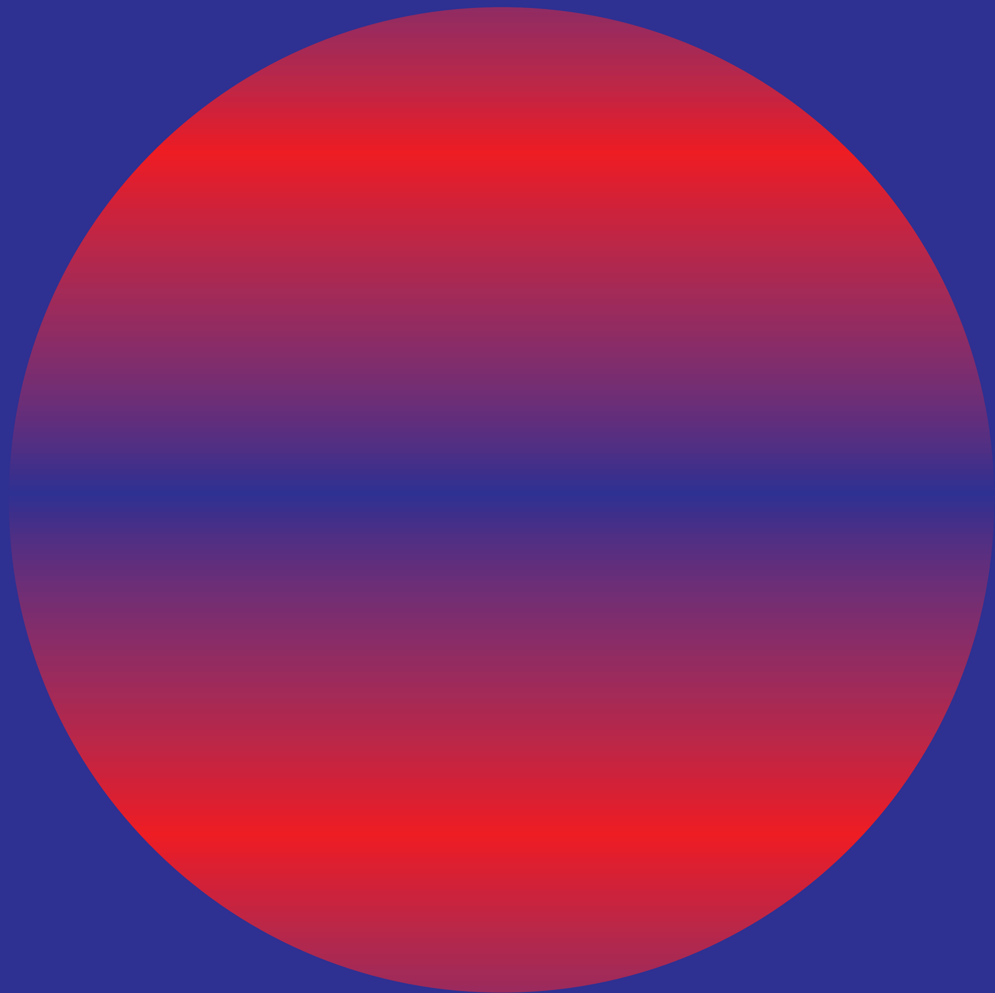
WMAP 3yr Data





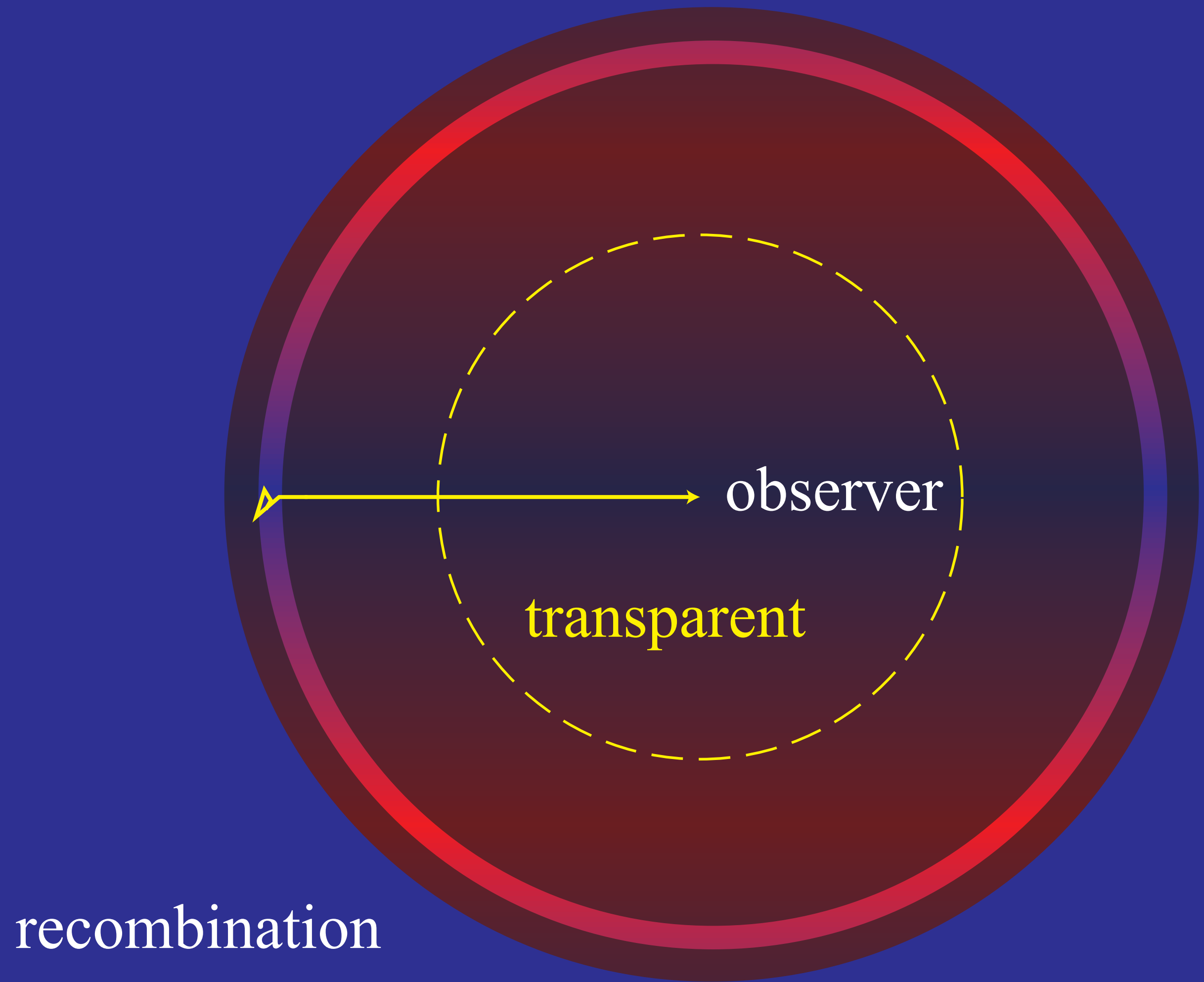
Temperature Inhomogeneity

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



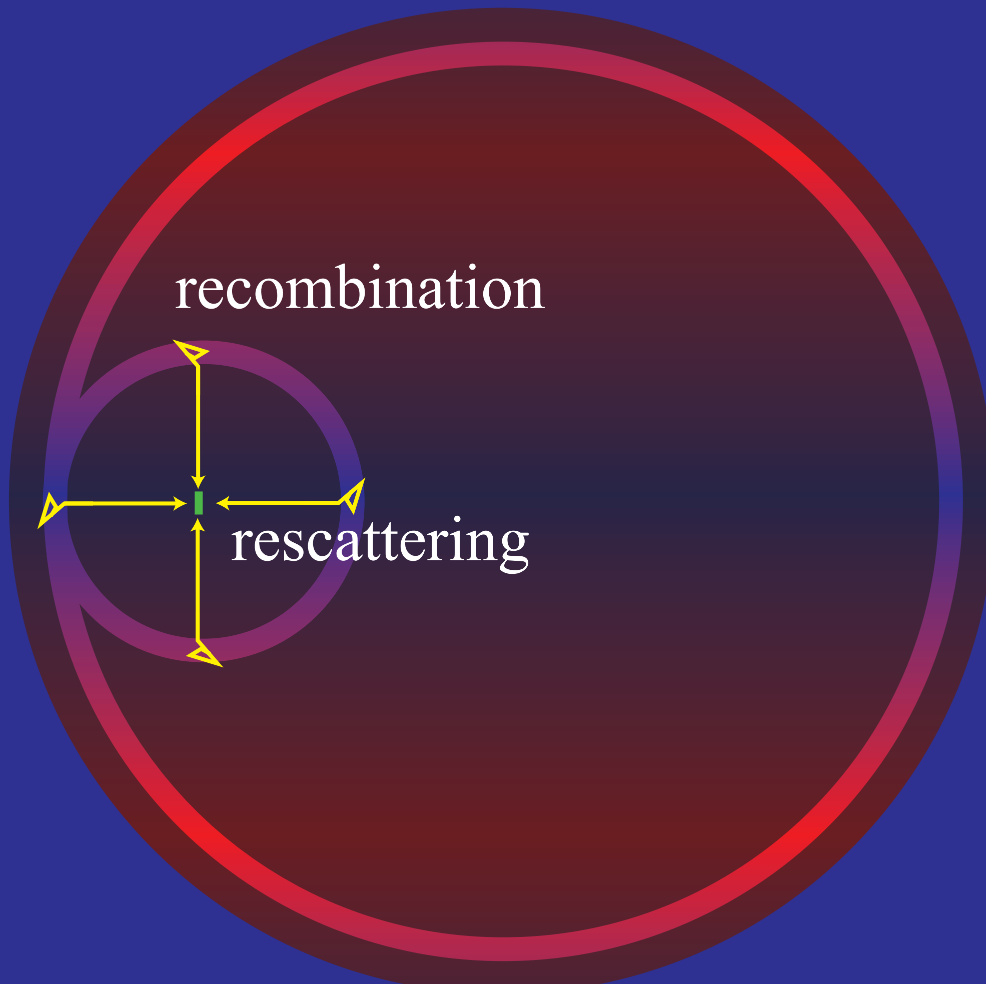
Locally Transparent

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



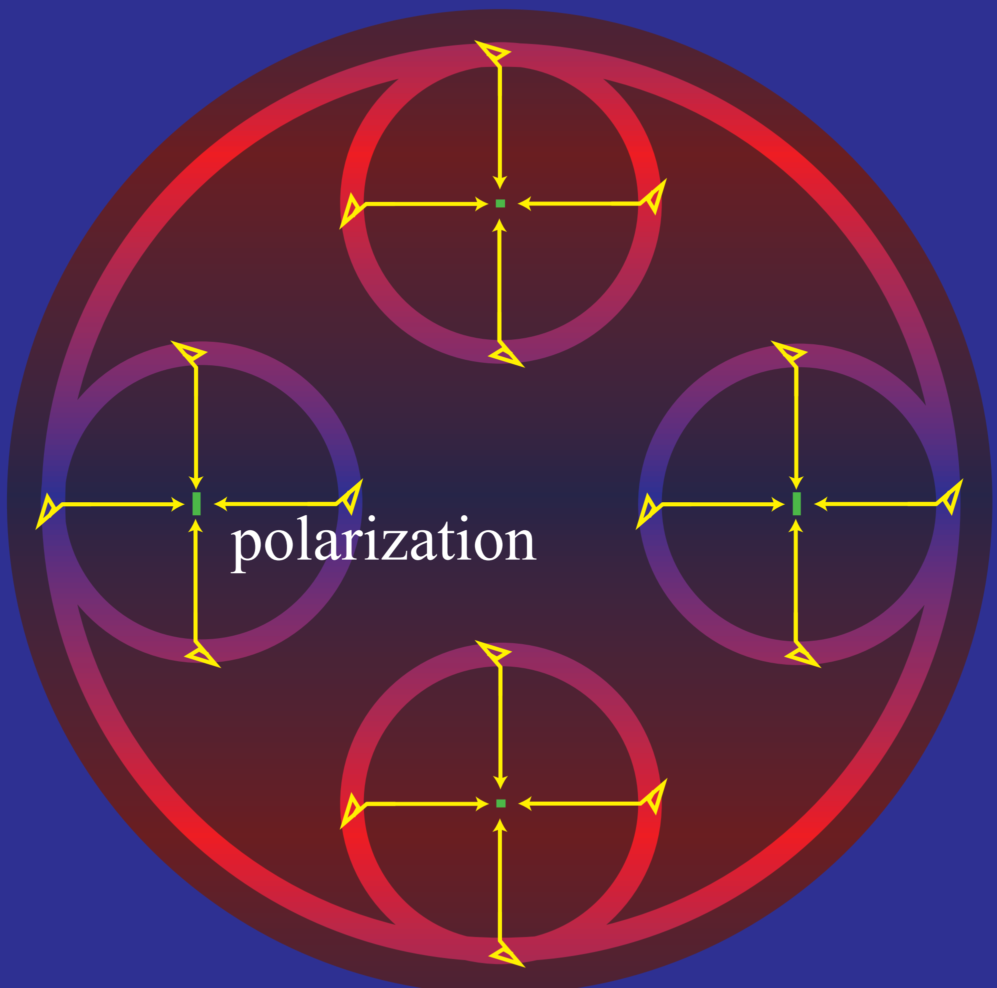
Reversed Expansion

- 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



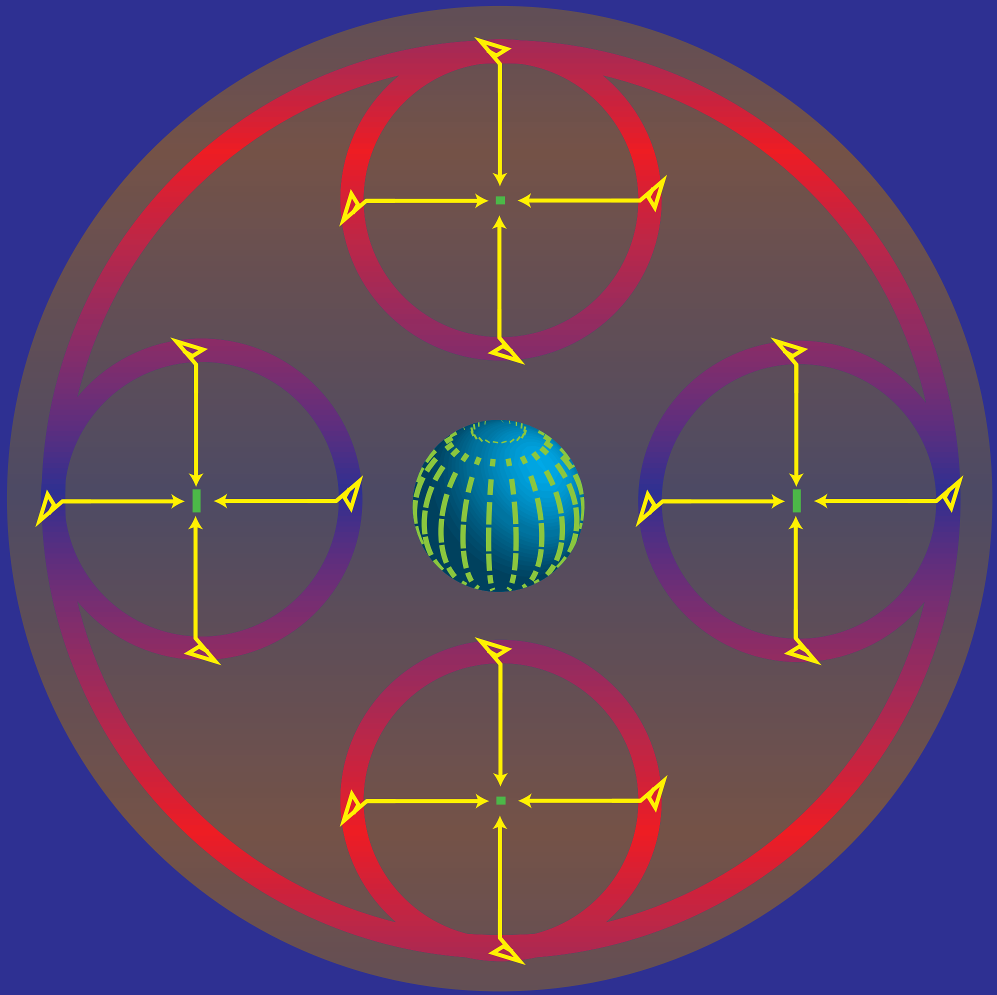
Polarization Anisotropy

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



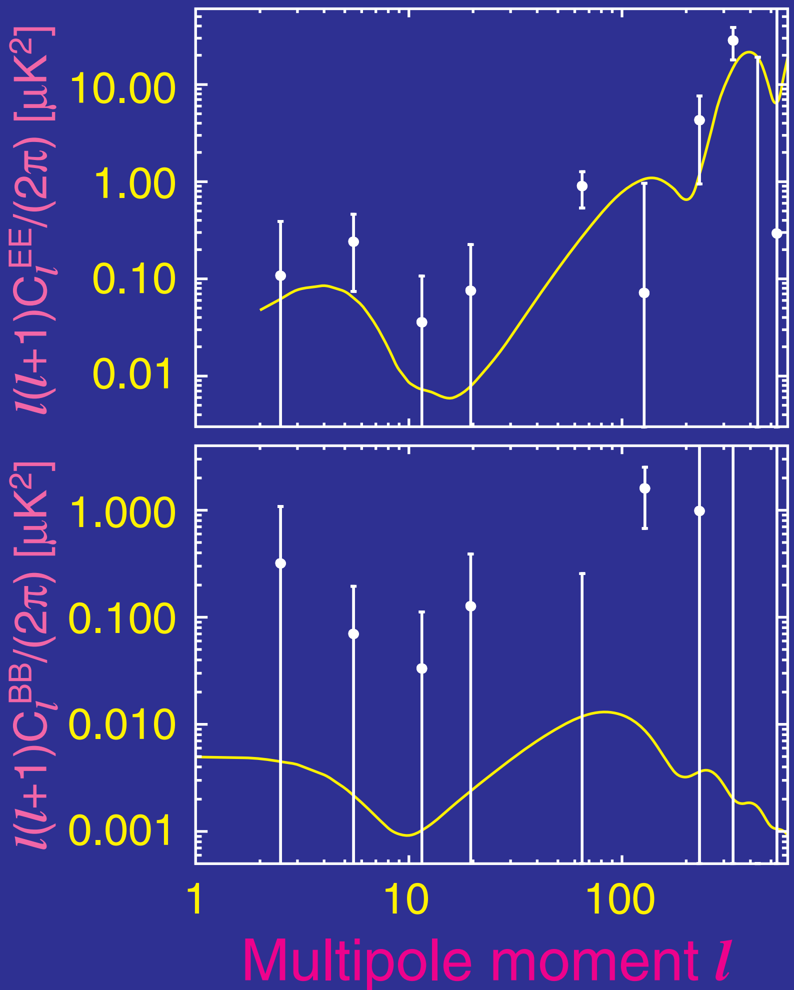
Temperature Correlation

- 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



Why Care?

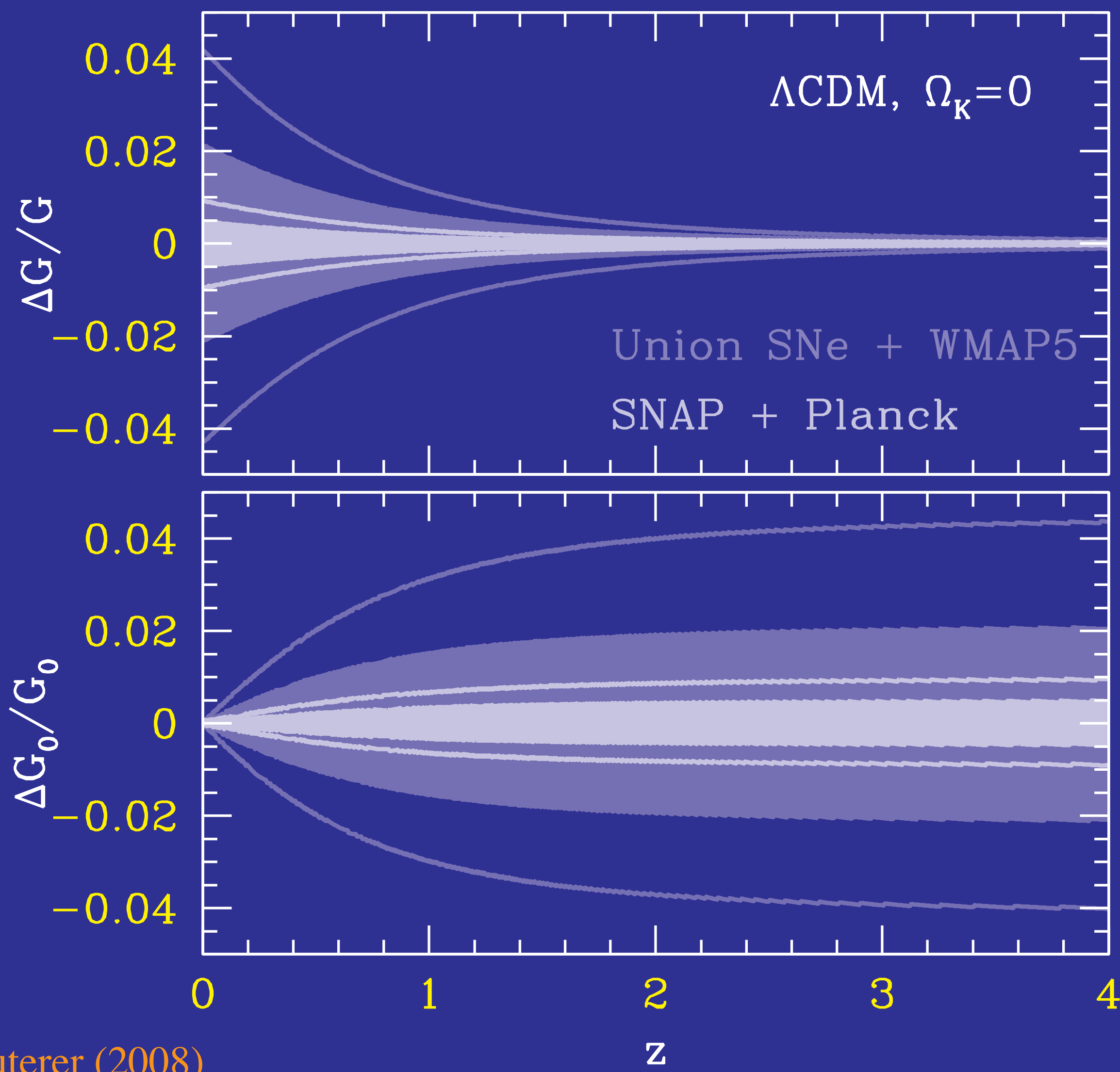
- Early ionization is puzzling if due to ionizing radiation from normal stars; may indicate more exotic physics is involved

- Reionization screens temperature anisotropy on small scales making the true amplitude of initial fluctuations larger by e^{τ}
- Measuring the growth of fluctuations is one of the best ways of determining the neutrino masses and the dark energy

- Offers an opportunity to study the origin of the low multipole statistical anomalies
- Presents a second, and statistically cleaner, window on gravitational waves from the early universe

Distance Predicts Growth

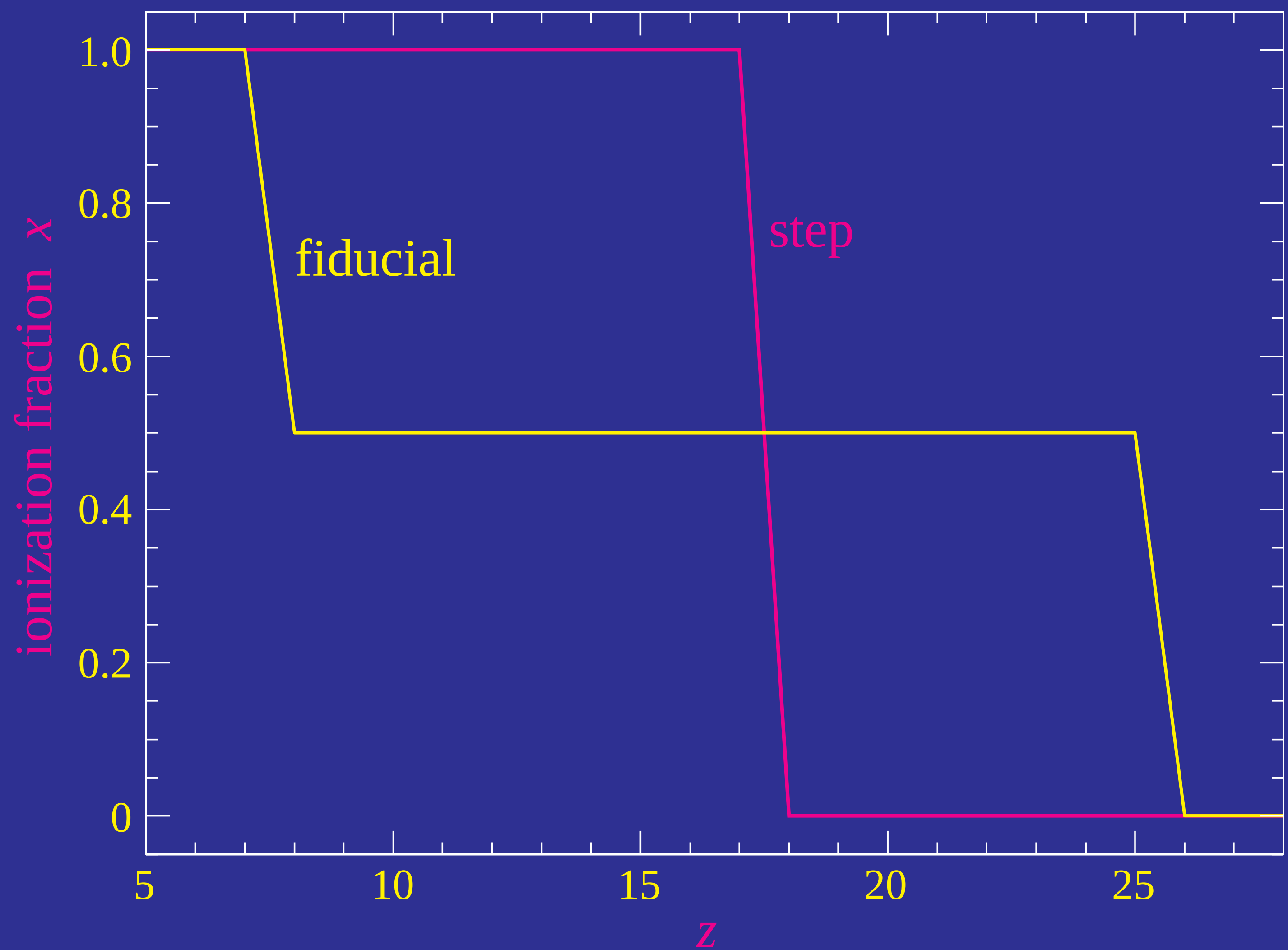
- With smooth dark energy, distance predicts scale-invariant growth to a few percent - a falsifiable prediction



Mortonson, Hu, Huterer (2008)

Ionization History

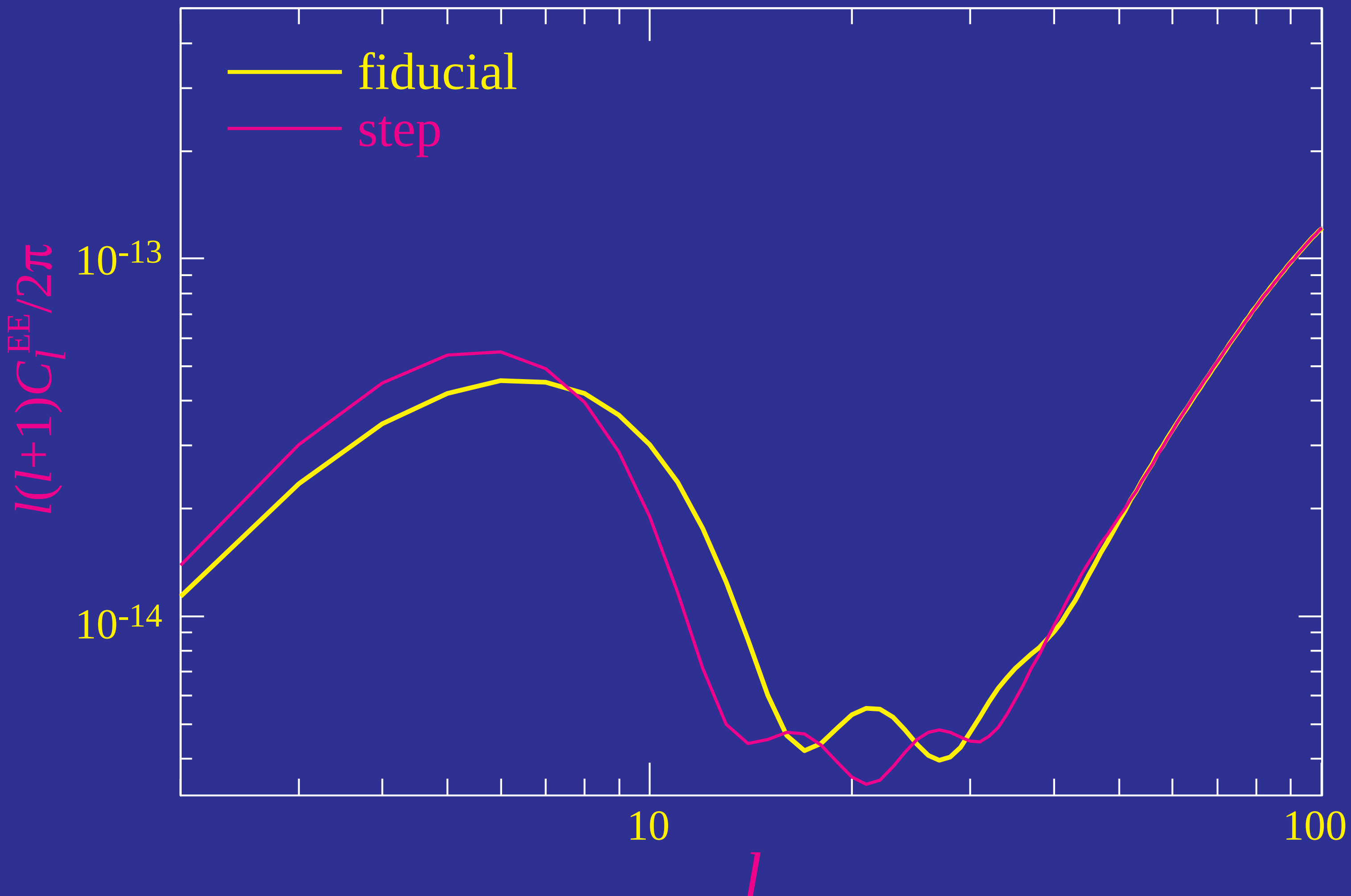
- Two models with same optical depth τ but different ionization history



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

Distinguishable History

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

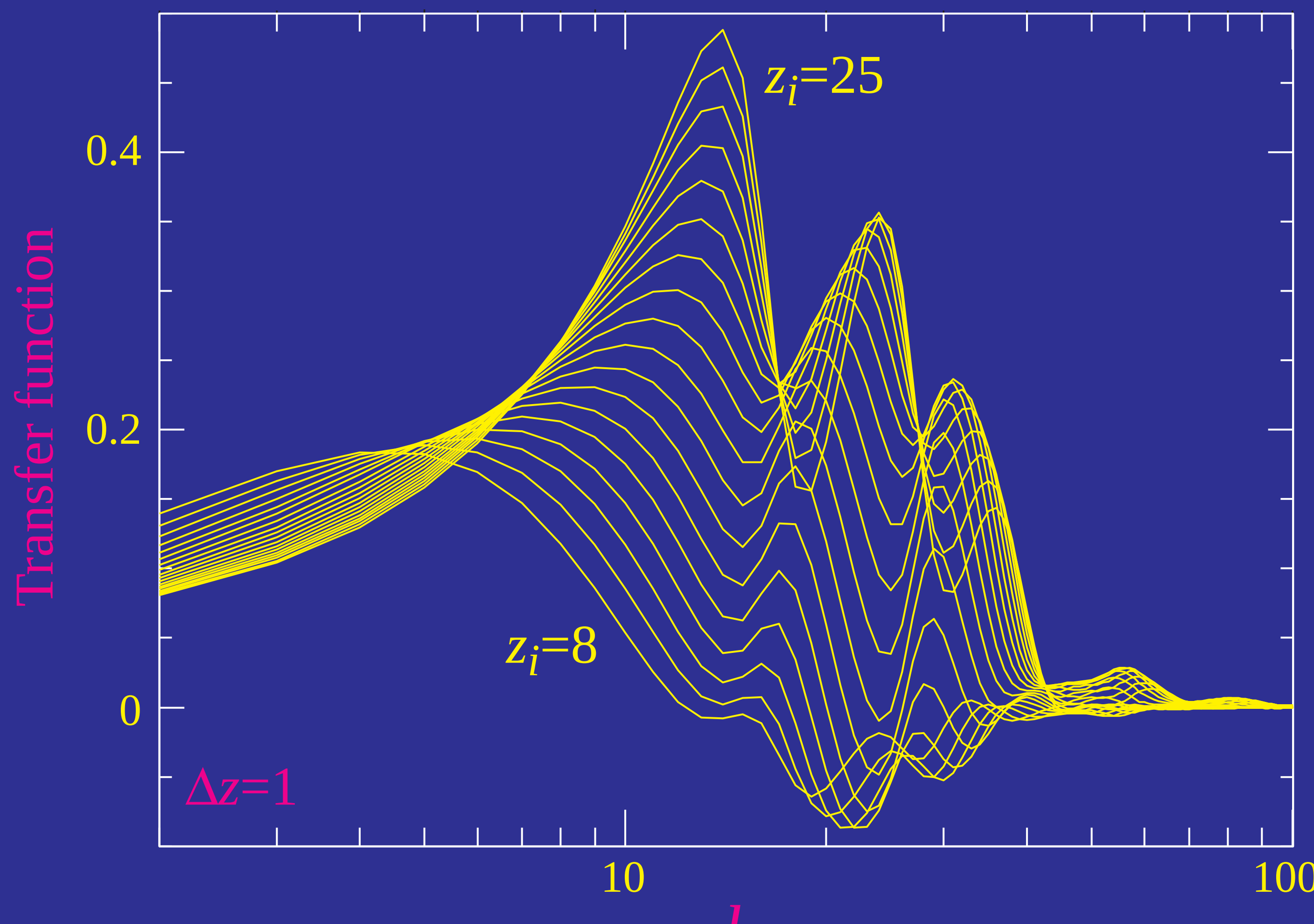


Kaplinghat et al. (2002); Hu & Holder (2003)

Transfer Function

- Linearized response to delta function ionization perturbation

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

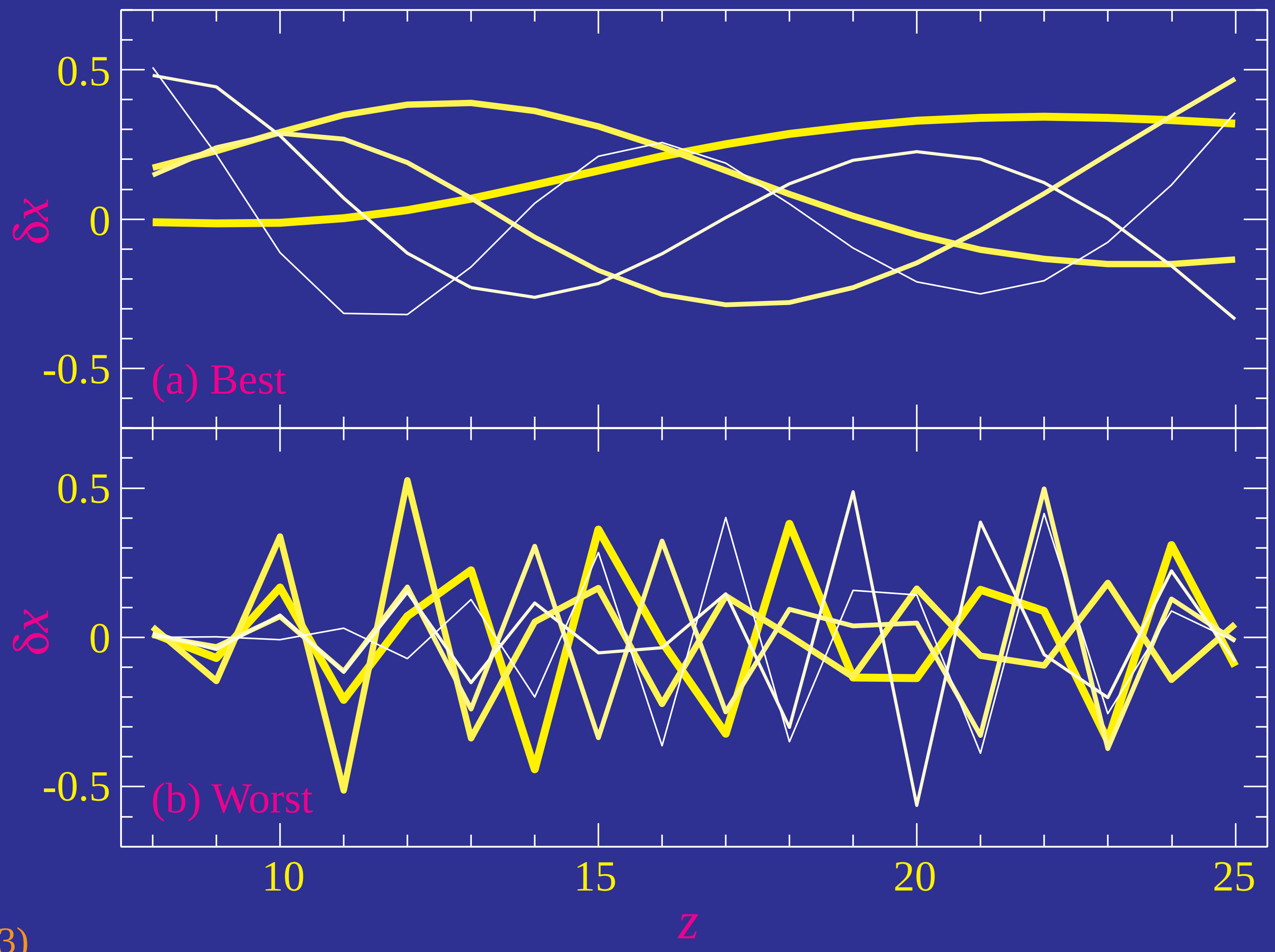


Hu & Holder (2003)

Principal Components

- Eigenvectors of the Fisher Matrix

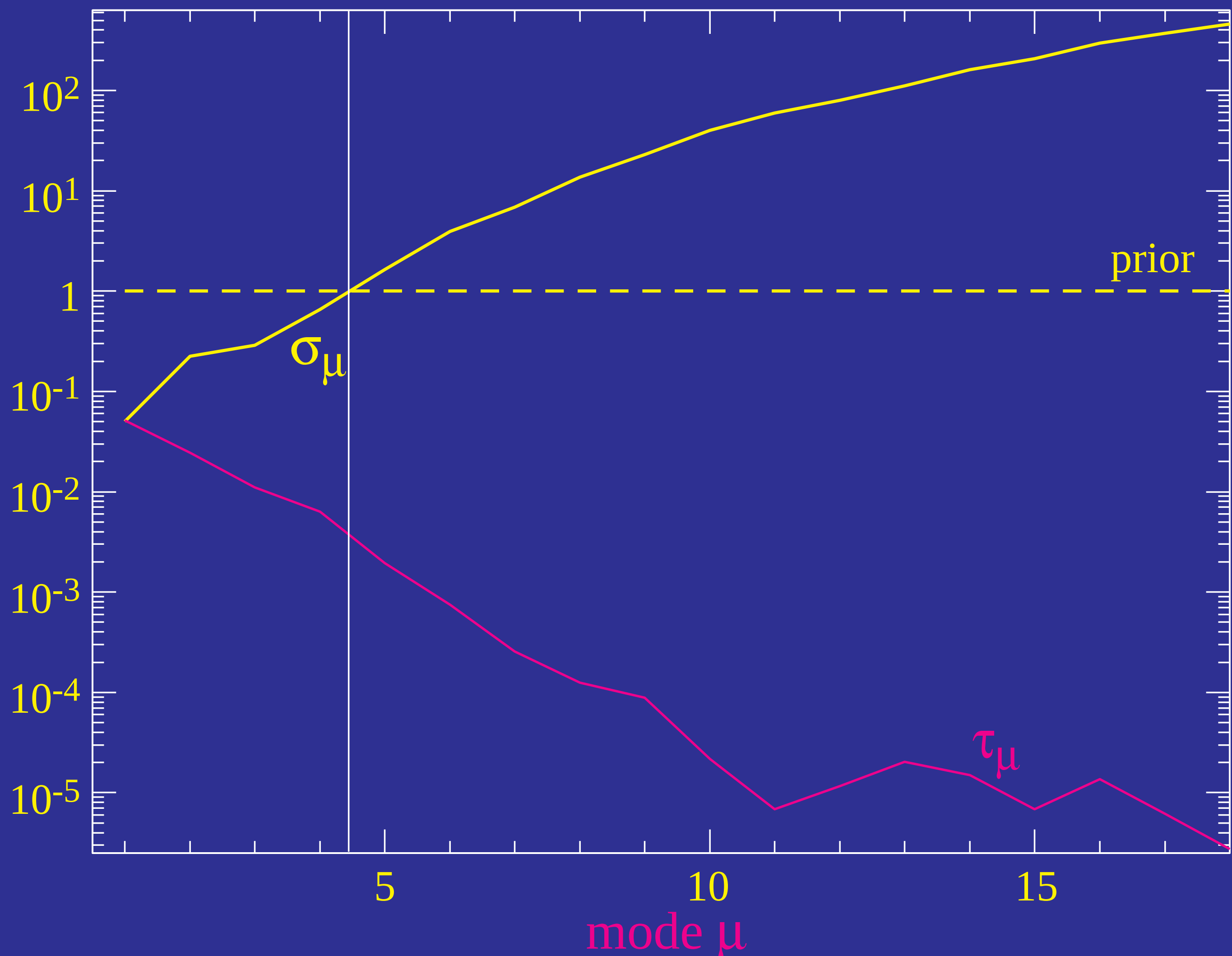
$$F_{ij} \equiv \sum_{\ell} (\ell + 1/2) T_{\ell i} T_{\ell j} = \sum_{\mu} S_{i\mu} \sigma_{\mu}^{-2} S_{j\mu}$$



Hu & Holder (2003)

Capturing the Observables

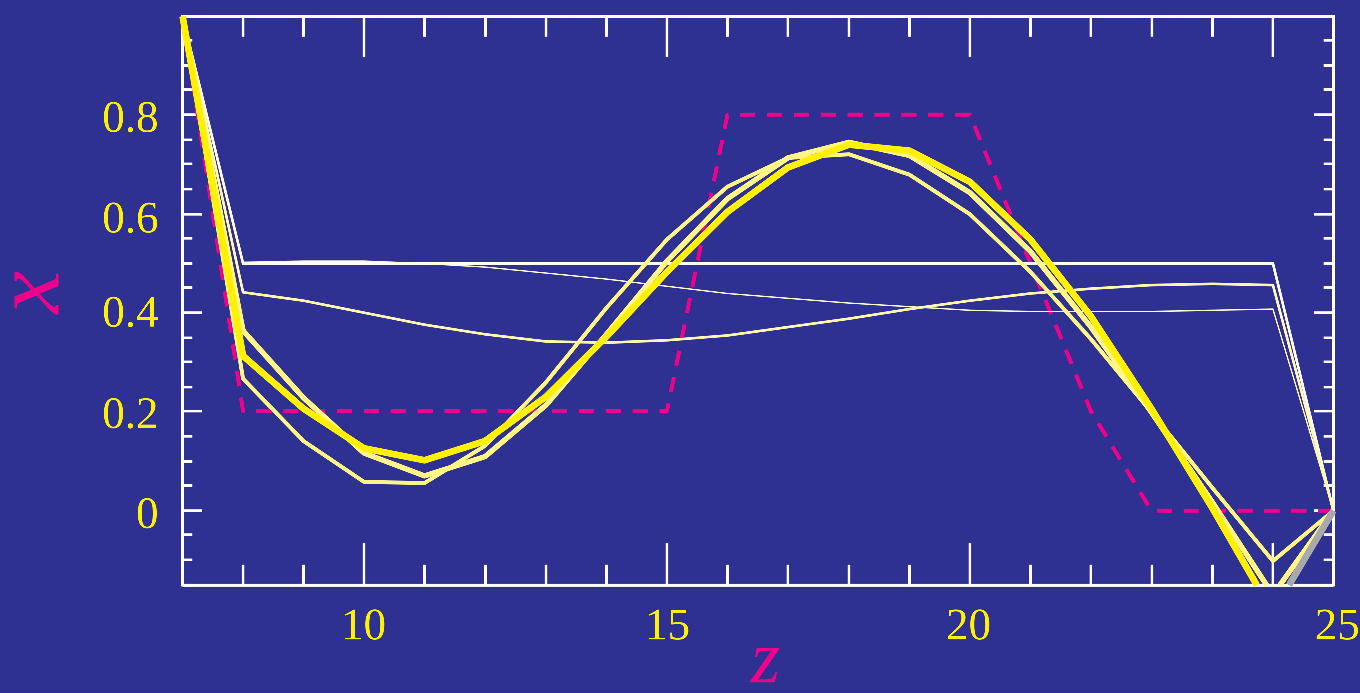
- First 5 modes have the information content and most of optical depth



Hu & Holder (2003)

Representation in Modes

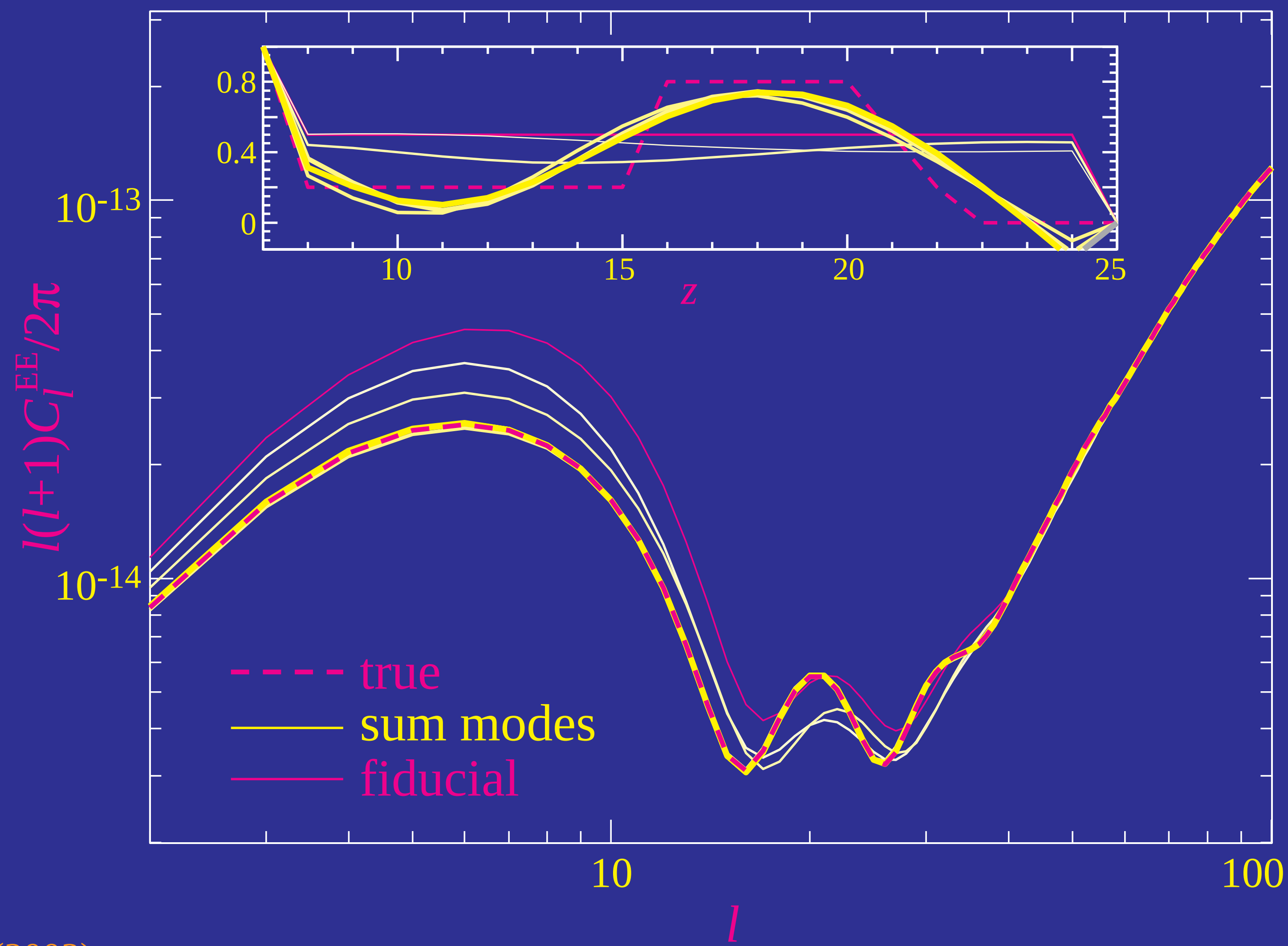
- Truncation at 5 modes leaves a low pass filtered of ionization history
- Ionization fraction allowed to go negative (Boltzmann code has negative sources)



Hu & Holder (2003)

Representation in Modes

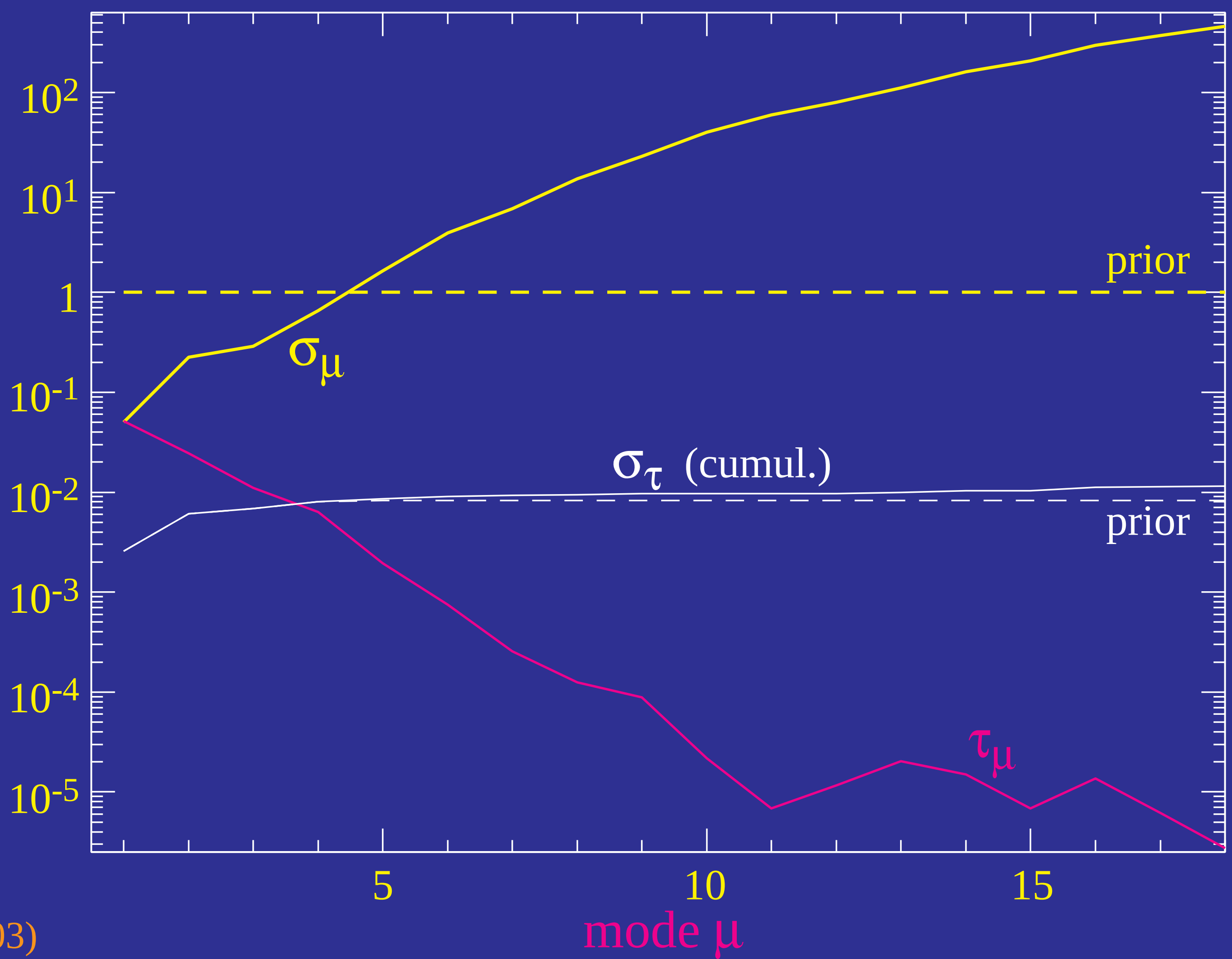
- Reproduces the power spectrum with sum over >3 modes
  more generally 5 modes suffices: e.g. total τ=0.1375 vs 0.1377



Hu & Holder (2003)

Total Optical Depth

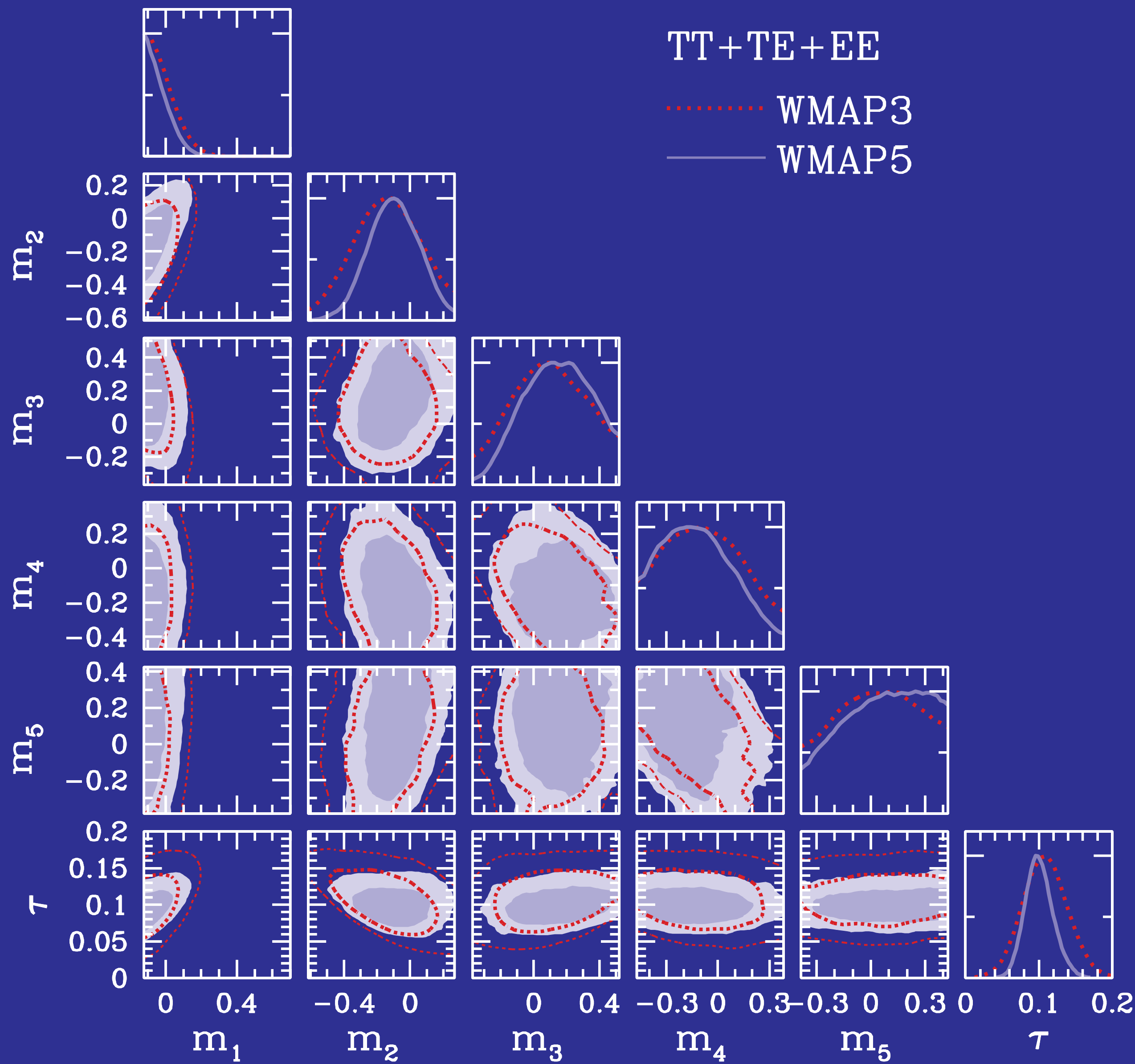
- Optical depth measurement unbiased
- Ultimate errors set by cosmic variance here 0.01
- Equivalently 1% measure of initial amplitude, impt for dark energy



Hu & Holder (2003)

WMAP5 Ionization PCs

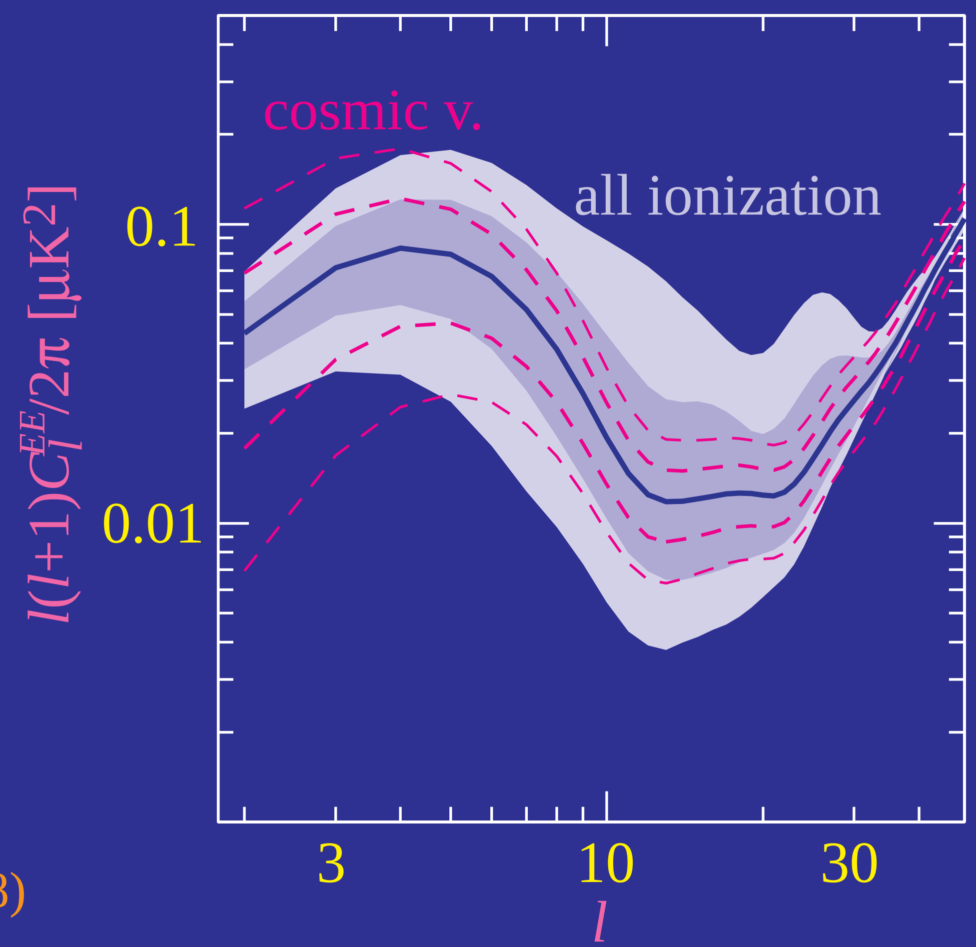
- Only first two modes constrained, τ=0.101±0.017



Mortonson & Hu (2008)

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

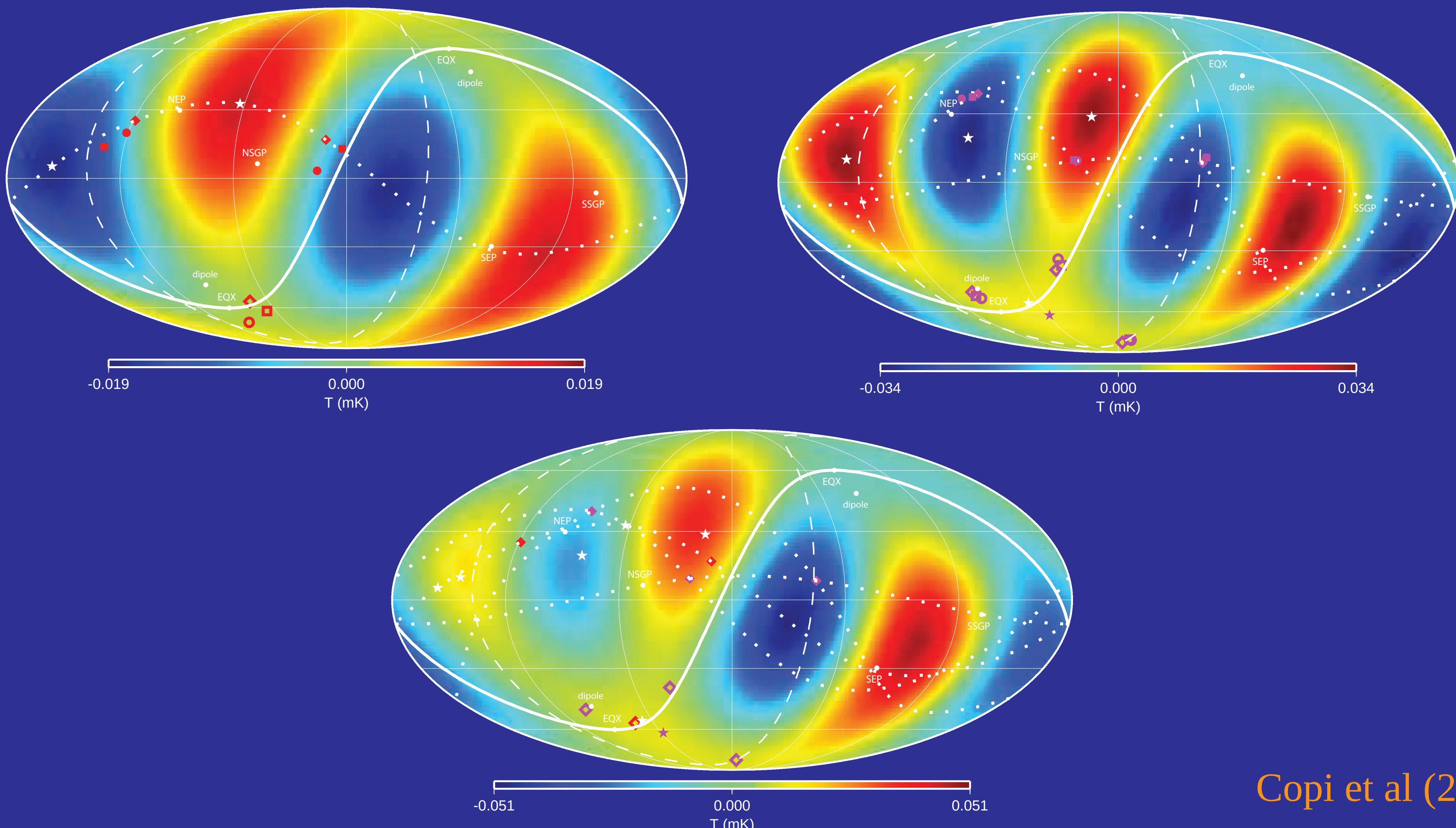


Mortonson & Hu (2008)

Large Scale Anomalies

Large Angle Anomalies

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

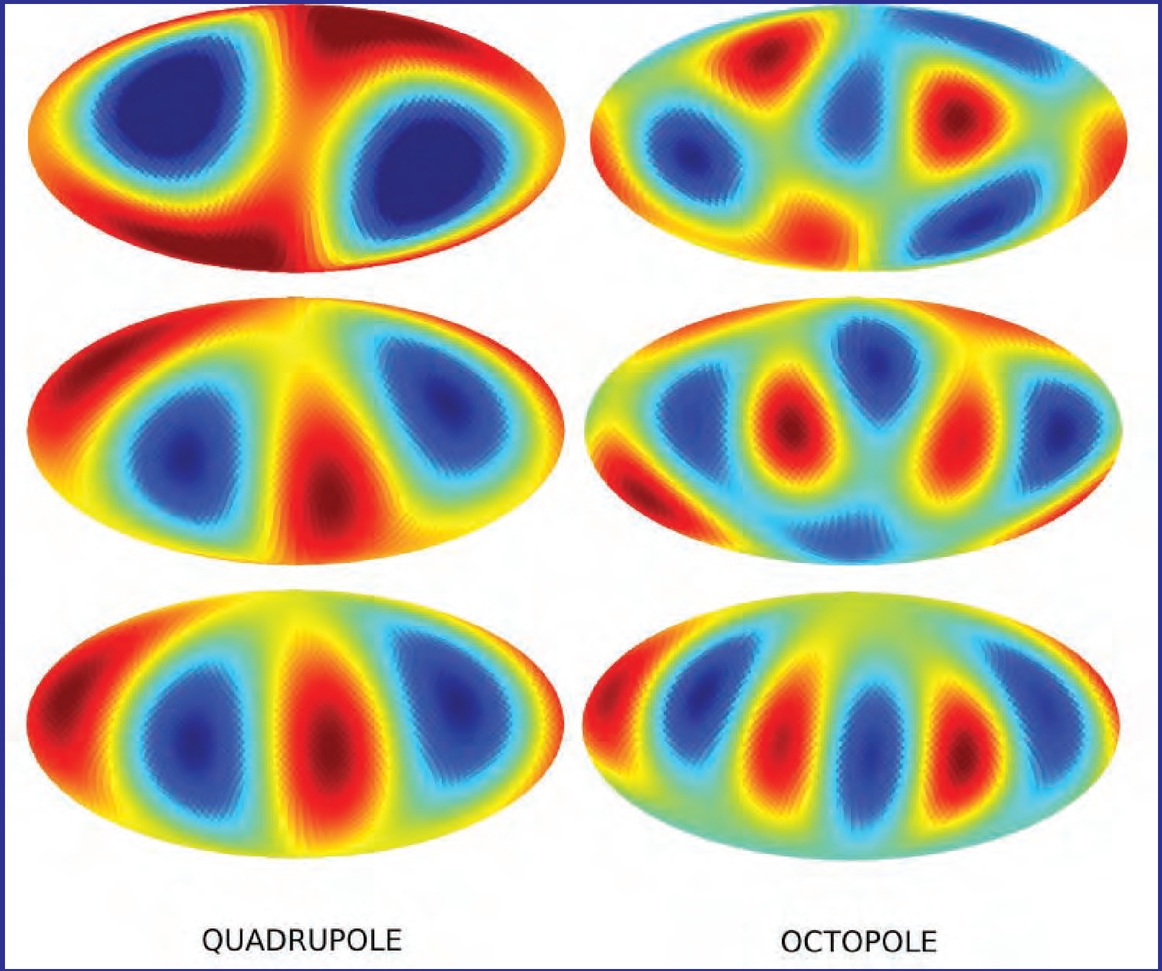


Copi et al (2006)

Polarization Tests

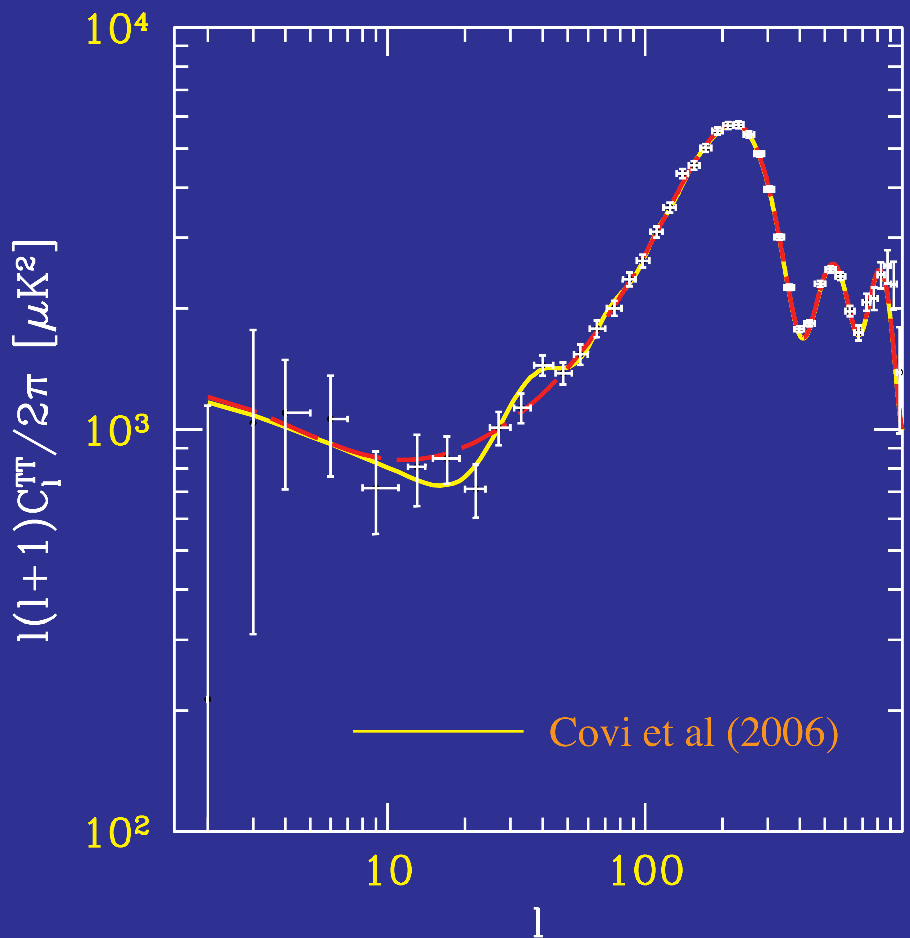
- Matching polarization anomalies if cosmological

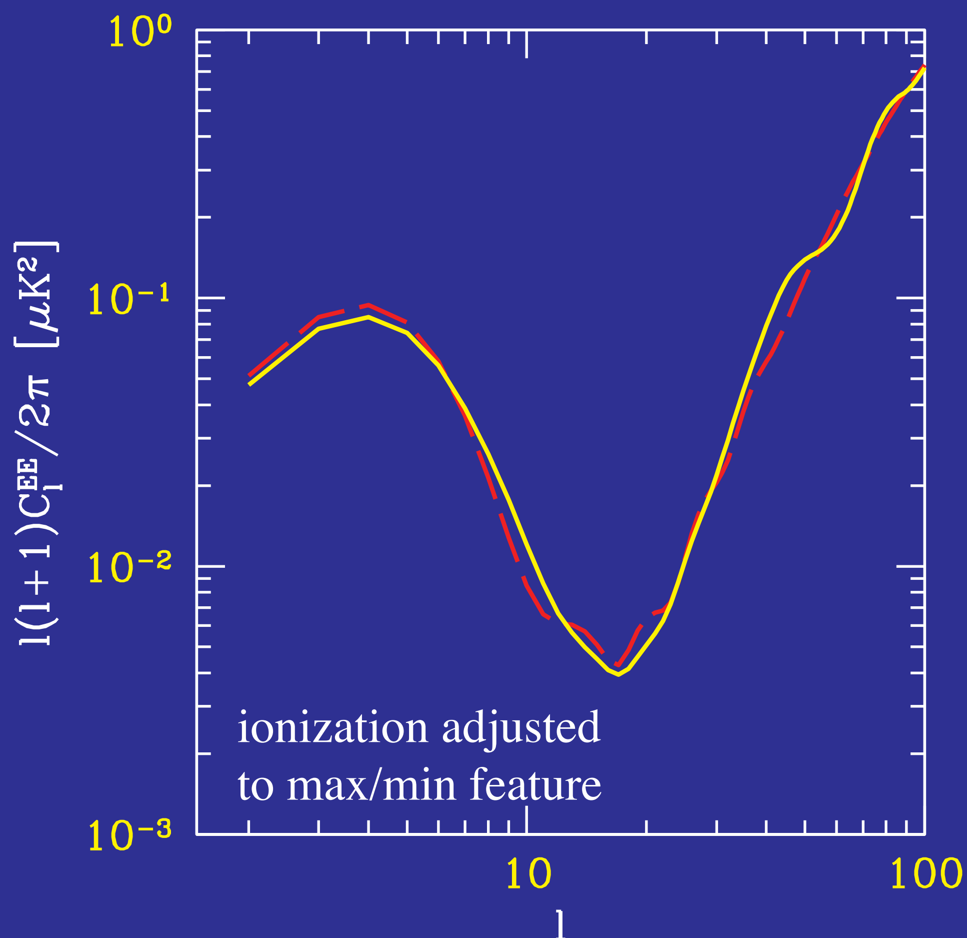
Dvorkin, Peiris, Hu (2007)



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)

Summary: Lecture I

- Reionization suppresses primary anisotropy as $e^{-\tau}$ so the precision of initial normalization and growth rate measurements depends on τ precision
- In temperature spectrum, suppression acts on small scalesand looks like tilt for WMAP (not Planck)
- Linear Doppler effect highly suppressed on small scales, leading order term is modulated effect: OV, kSZ, patchy reionization
- Rescattering of quadrupole anisotropy leads to linear polarization at large angles
- Shape of polarization spectrum carries sufficient information to measure τ independently of ionization history (through PCs)
- If large angle anomalies are cosmological, they will be reflected in polarization