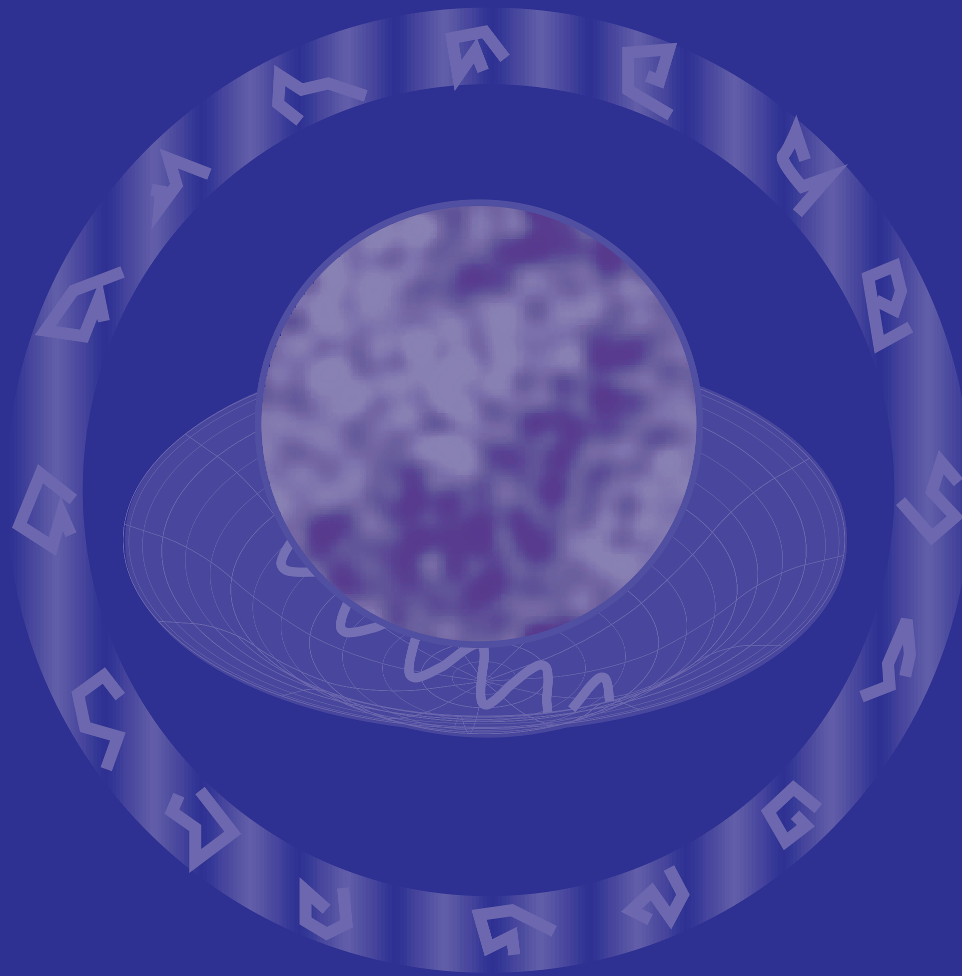
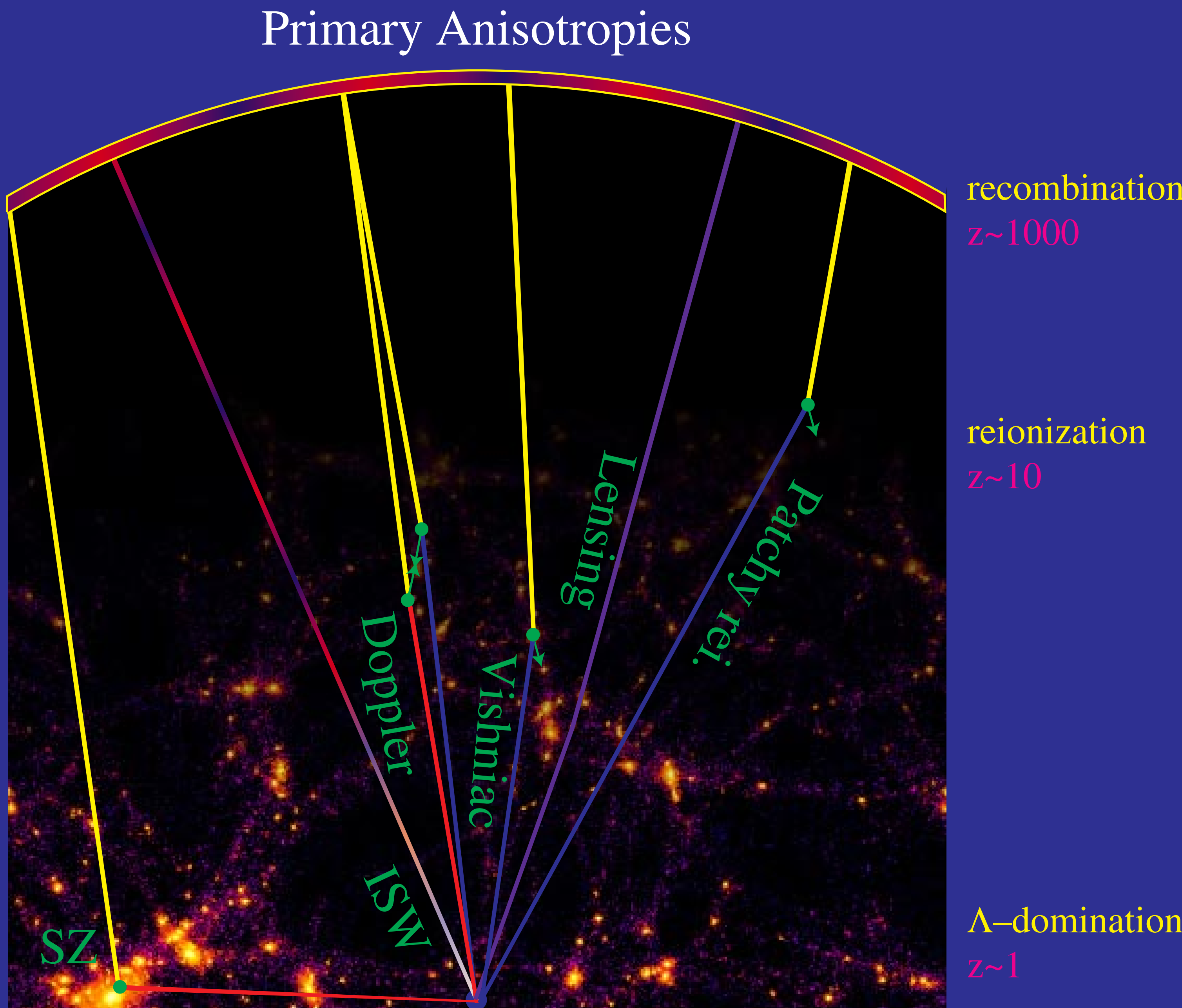
The Physics of Secondary Anisotropies

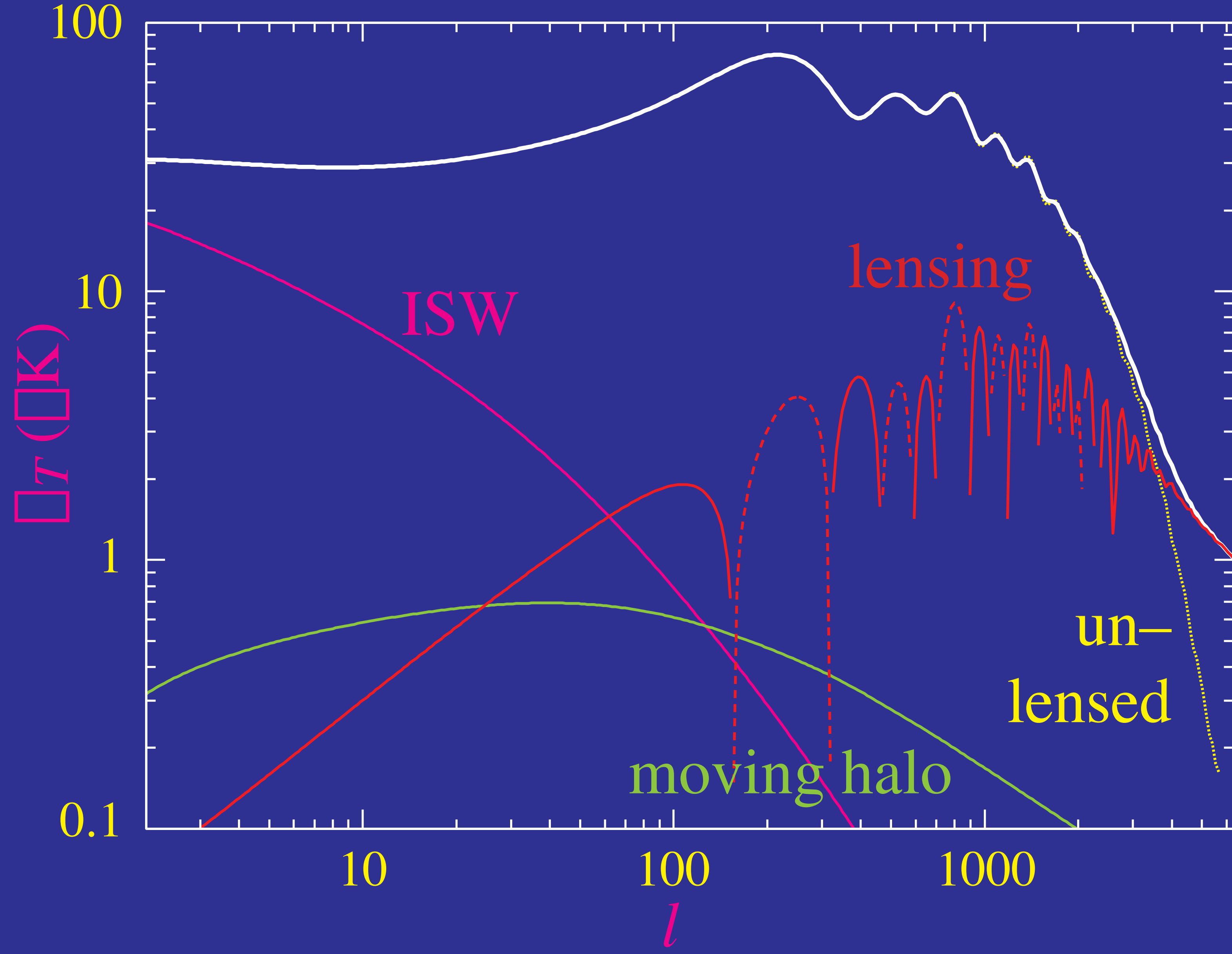


Wayne Hu

Physics of Secondary Anisotropies



Gravitational Secondaries



Structure Formation & CMB

CMB = Initial Conditions for Structure

- COBE detection provides normalization of potential fluctuations at z=1000
- Acoustic oscillations imprint small baryon wiggles in matter power spectrum

CMB = Initial Conditions for Structure

- COBE detection provides normalization of potential fluctuations at z=1000
- Acoustic oscillations imprint small baryon wiggles in matter power spectrum
- CMB energy density causes a $(k_{\rm eq}/k)^4$ suppression of small–scale power
- Implies a bottom-up or hierarchical structure formation

CMB = Initial Conditions for Structure

- COBE detection provides normalization of potential fluctuations at z=1000
- Acoustic oscillations imprint small baryon wiggles in matter power spectrum

- CMB energy density causes a $(k_{eq}/k)^4$ suppression of small–scale power
- Implies a bottom-up or hierarchical structure formation

- First objects form at z~10–20
- Reionize the universe by z~6

- Dark energy slows growth of structure near z~1
- Non-linear scale currently ~0.1 h Mpc^{-1}

Acoustic Peaks in the Matter

- Baryon density & velocity oscillates with CMB
- Baryons decouple at $\tau / R \sim 1$, the end of Compton drag epoch
- Decoupling: $\delta_b(\mathrm{drag}) \sim V_b(\mathrm{drag})$, but not frozen
- Continuity: $\dot{\delta}_b = -kV_b$
- Velocity Overshoot Dominates: $\delta_b \sim V_b(\mathrm{drag})\, k\eta \gg \delta_b(\mathrm{drag})$
- Oscillations $\pi/2$ out of phase with CMB
- Infall into potential wells (DC component)

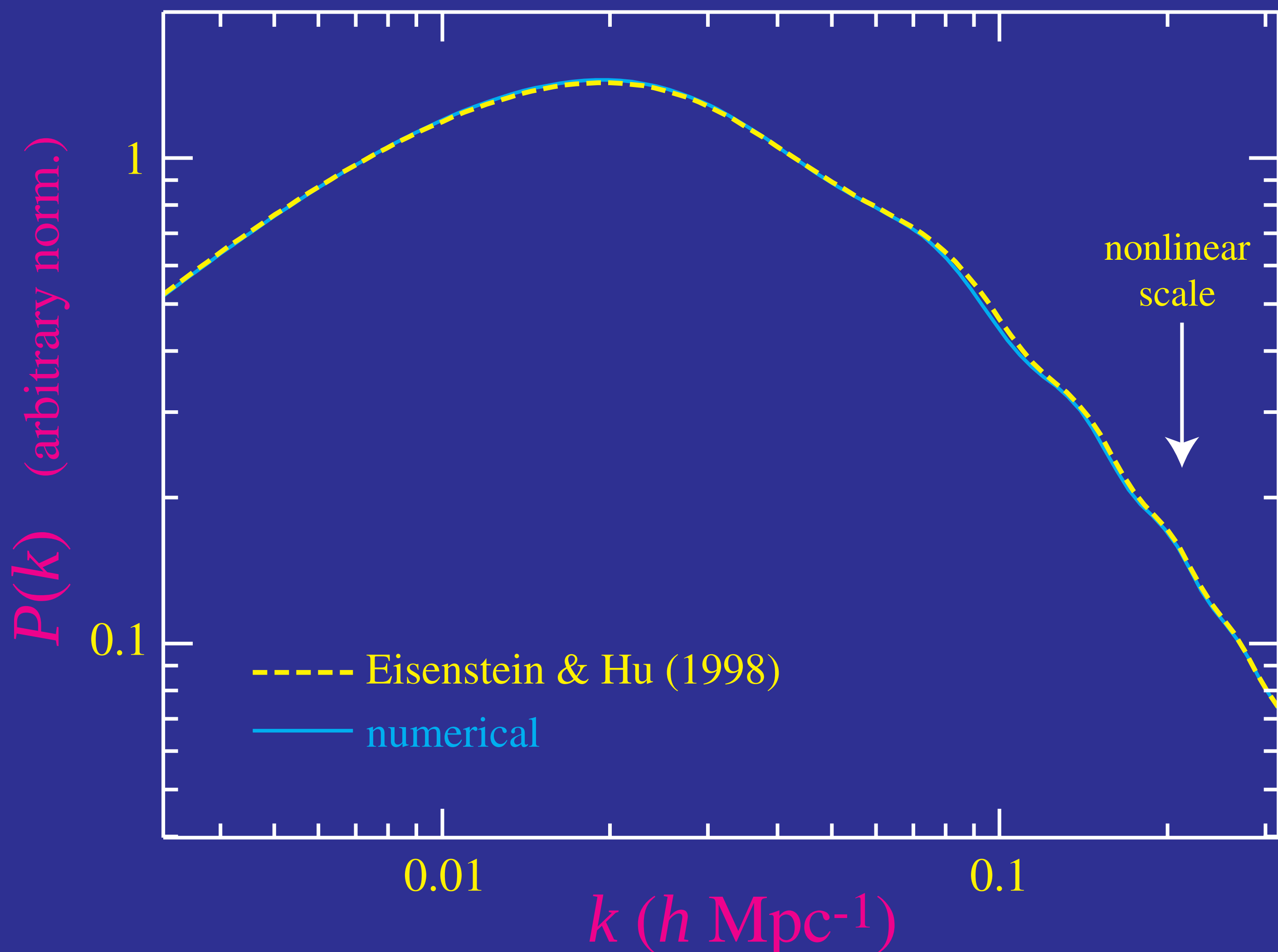
End of Drag Epoch

Velocity Overshoot + Infall

Hu & Sugiyama (1996)

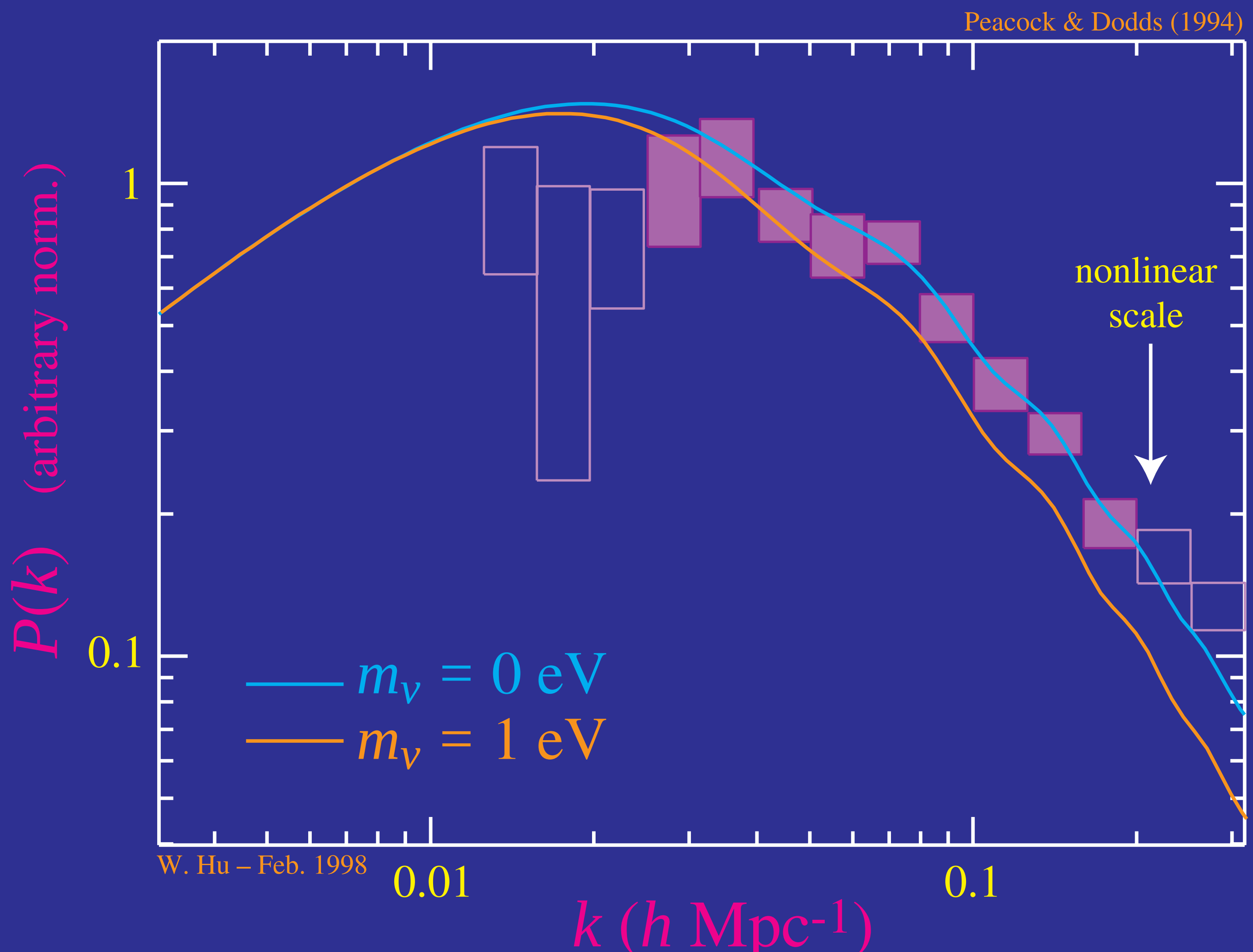
Features in the Power Spectrum

- Features in the linear power spectrum
- Break at sound horizon
- Oscillations at small scales; washed out by nonlinearities



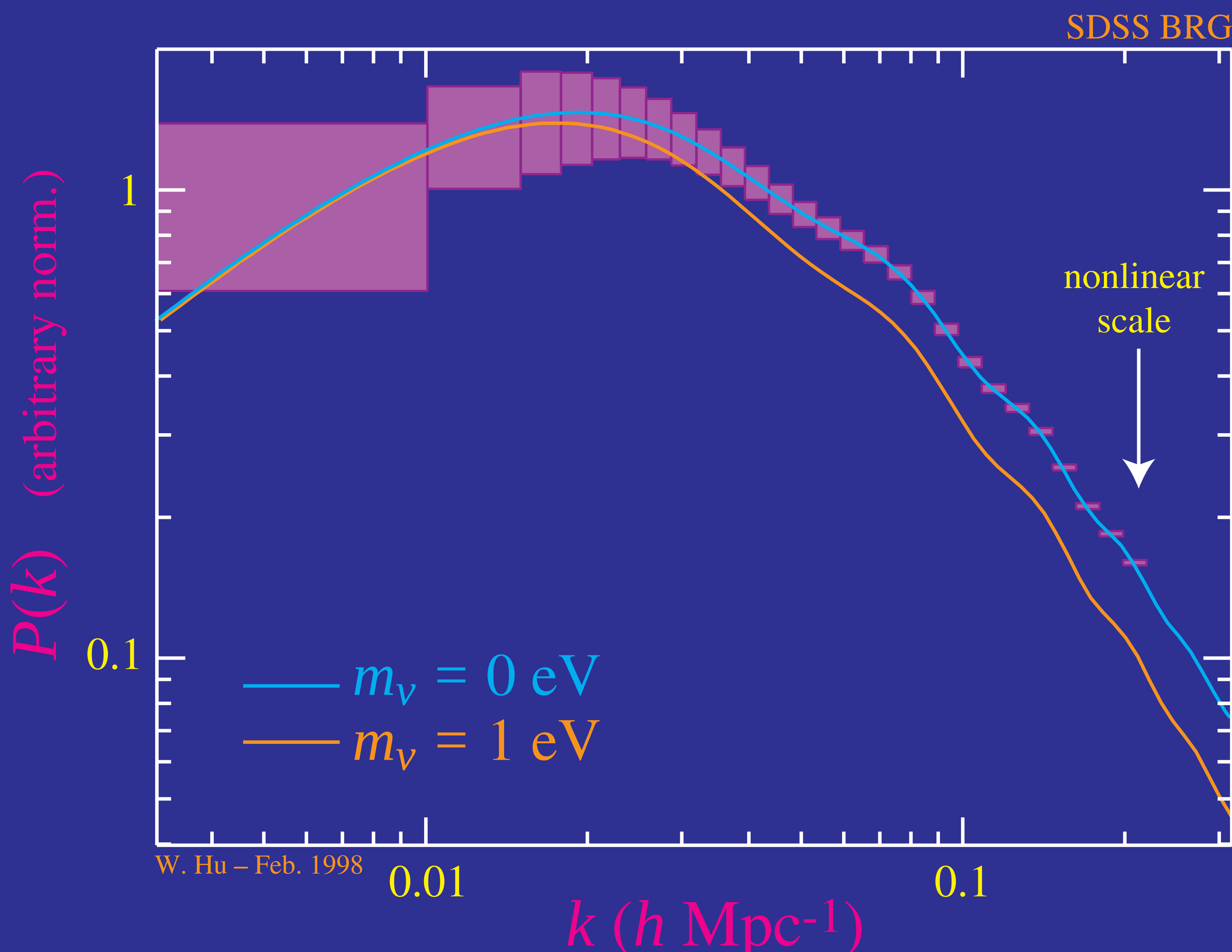
Features in the Power Spectrum

- Features in the linear power spectrum
- Break at sound horizon
- Oscillations at small scales; washed out by nonlinearities



Features in the Power Spectrum

- **Features** in the linear power spectrum
- **Break** at sound horizon
- **Oscillations** at small scales; washed out by nonlinearities

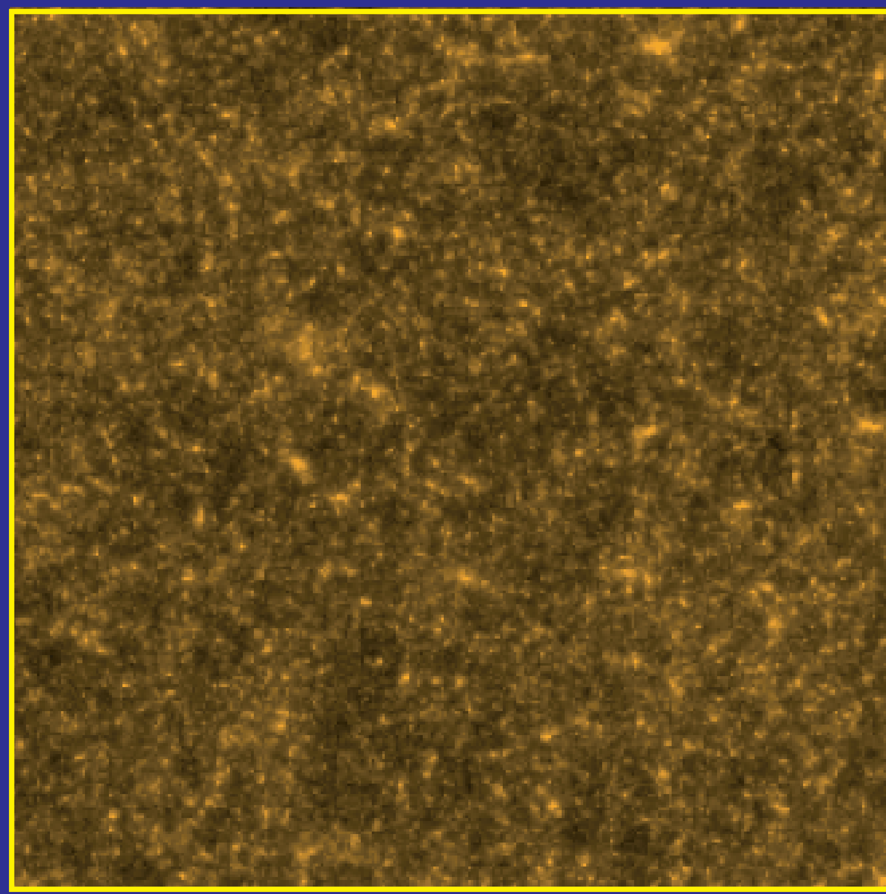


Hierarchical Evolution

Halo Model

- Model density field as (linearly) clustered NFW halos with mass function

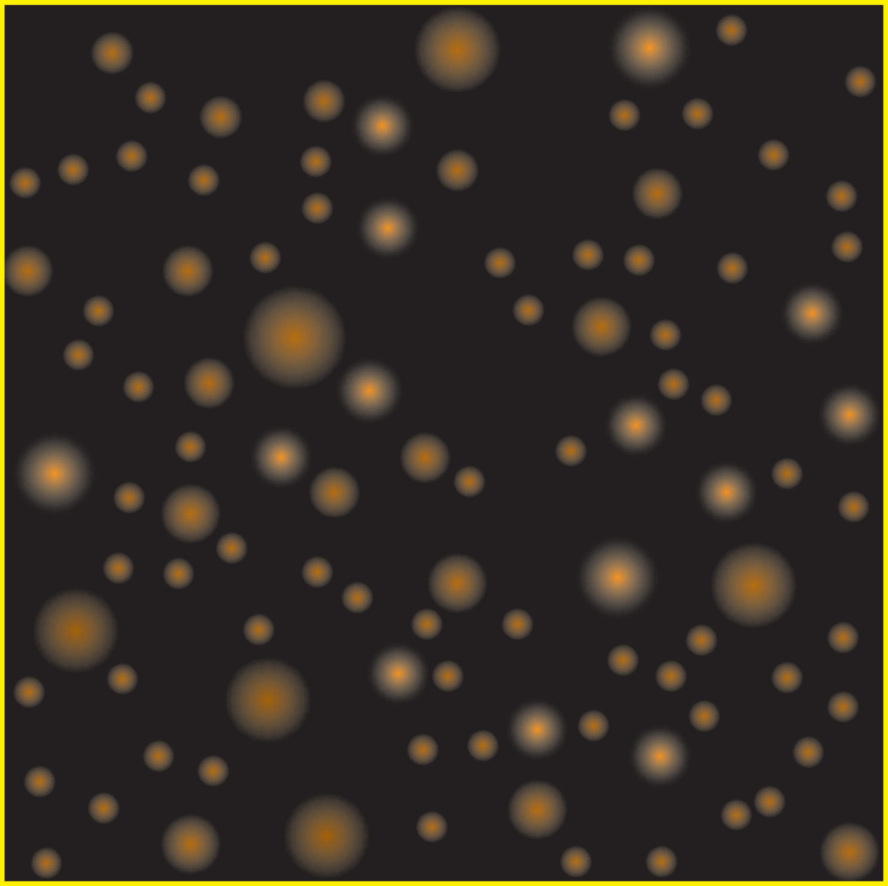
Simulation



Halo Model

- Model density field as (linearly) clustered NFW halos with mass function

Halo Model



Integrated Sachs-Wolfe Effect

Smooth Energy Density & Potential Decay

- Regardless of the equation of state an energy component that clusters preserves an approximately constant gravitational potential (formally Bardeen curvature ζ)

Smooth Energy Density & Potential Decay

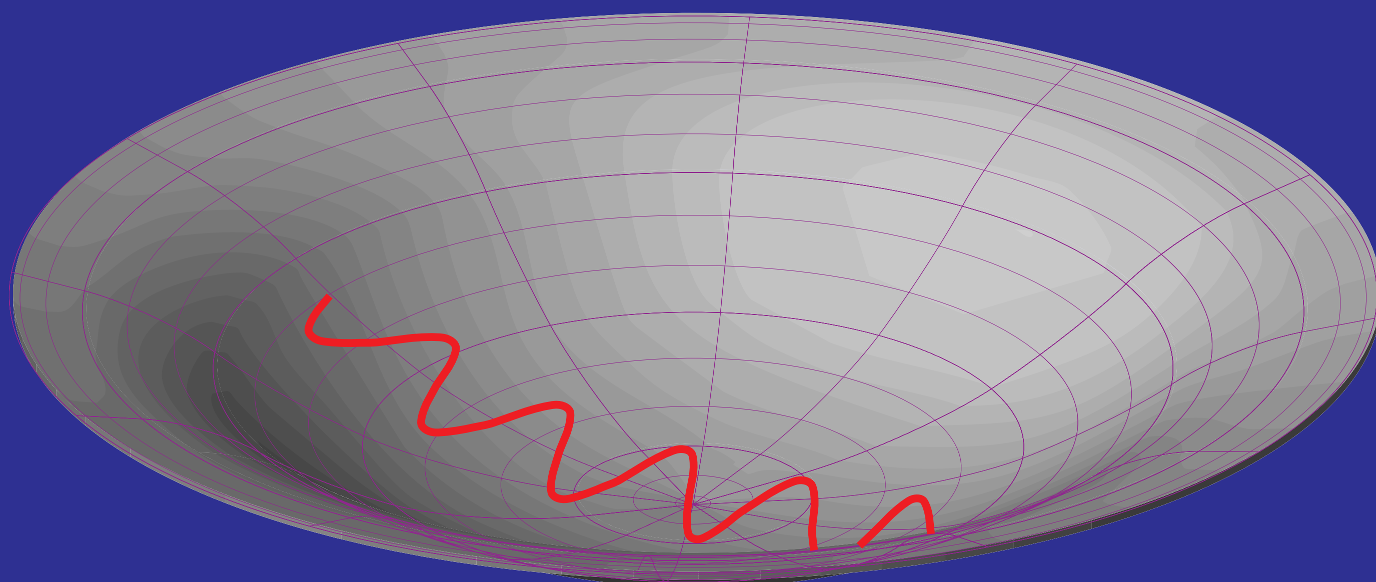
- Regardless of the equation of state an energy component that clusters preserves an approximately constant gravitational potential (formally Bardeen curvature ζ)
- A smooth component contributes
  density ρ to the expansion
  but not
  density fluctuation $\delta\rho$ to the Poisson equation
- Imbalance causes potential to decay once smooth component dominates the expansion

Smooth Energy Density & Potential Decay

- Regardless of the equation of state an energy component that clusters preserves an approximately constant gravitational potential (formally Bardeen curvature ζ)
- A smooth component contributes
  density ρ to the expansion
  but not
  density fluctuation $\delta\rho$ to the Poisson equation
- Imbalance causes potential to decay once smooth component dominates the expansion
- Scalar field dark energy (quintessence) is smooth out to the horizon scale (sound speed $c_s=1$)
- Potential decay measures the clustering properties and hence the particle properties of the dark energy

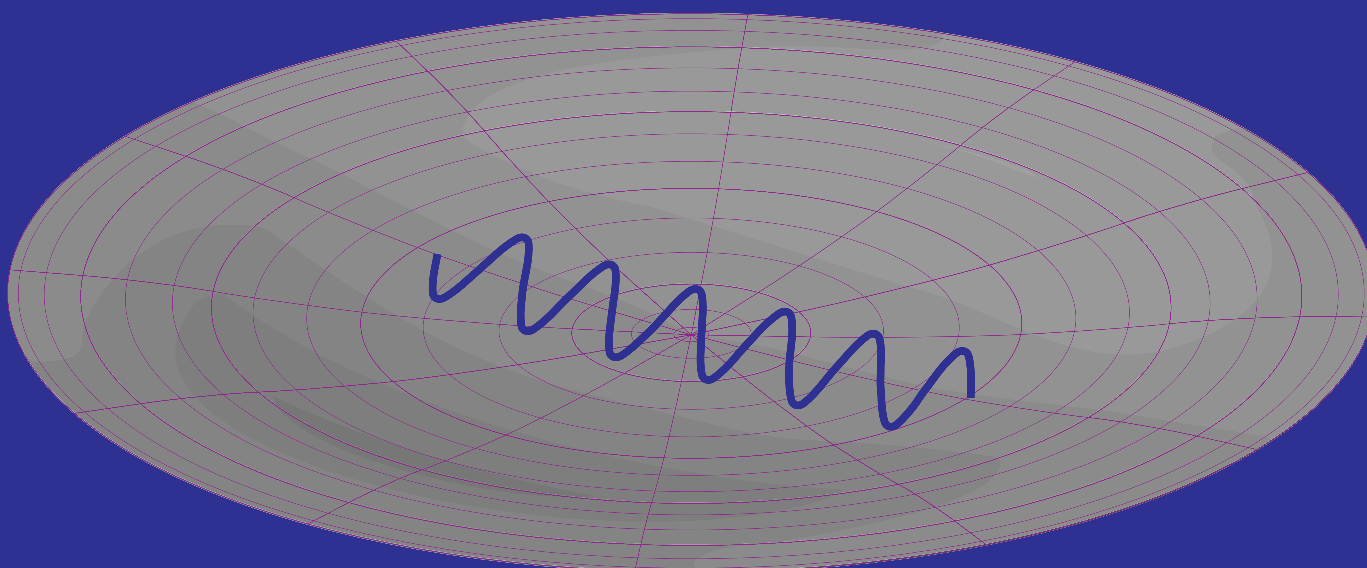
ISW Effect

- 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



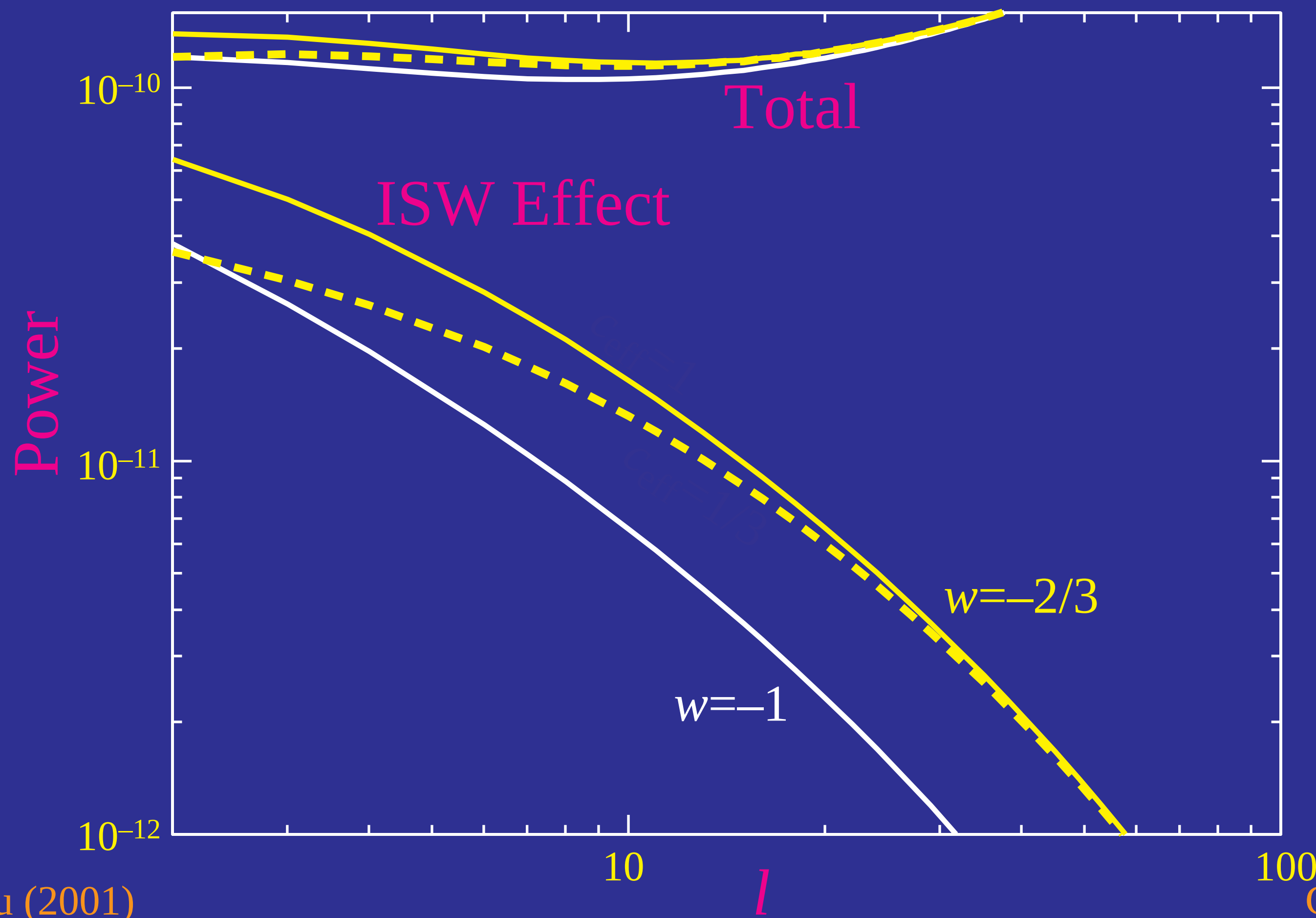
ISW Effect

- 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



ISW Effect and Dark Energy

- Raising equation of state increases redshift of dark energy domination and raises the ISW effect
- Lowering the sound speed increases clustering and reduces ISW effect at large angles

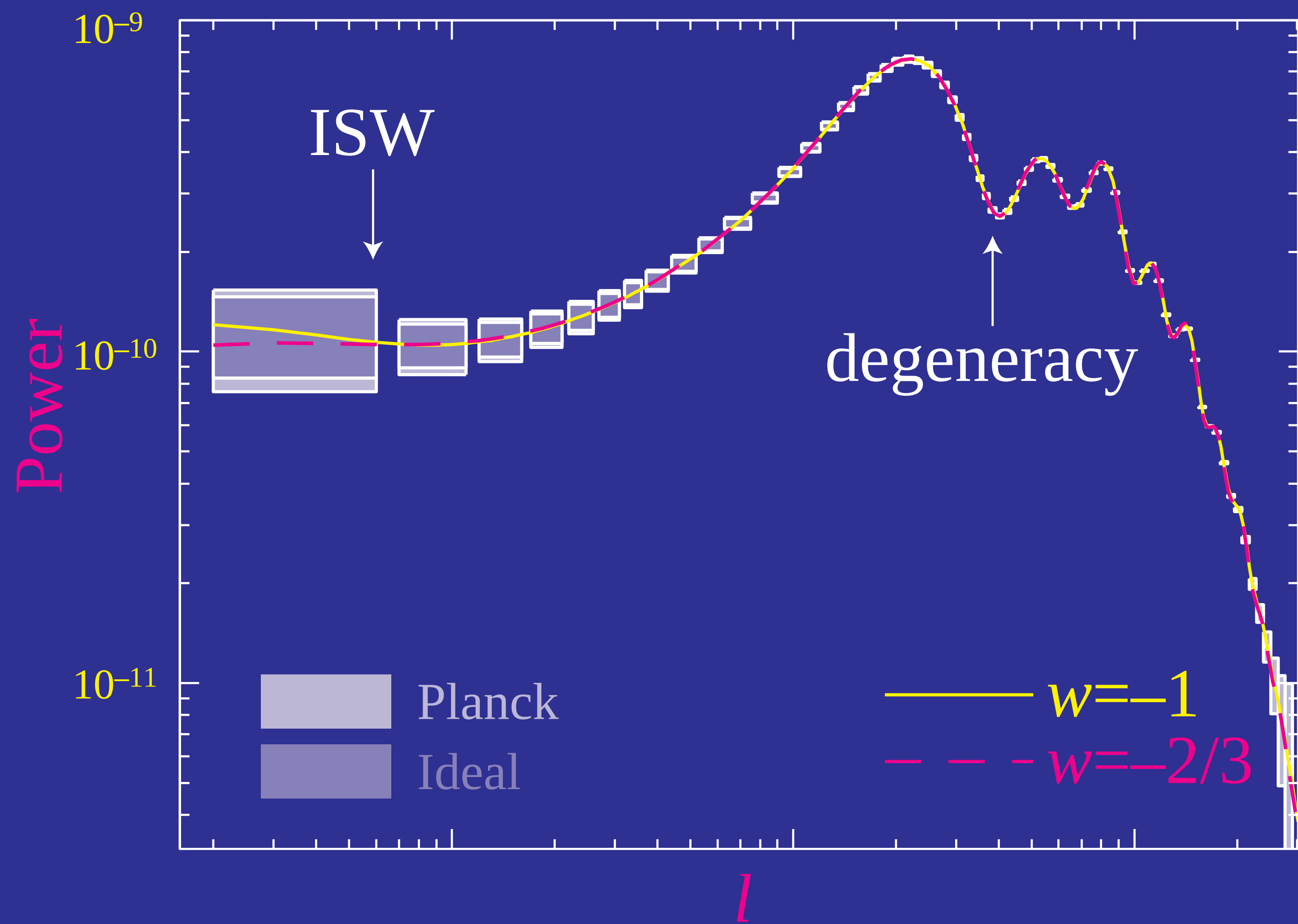


Hu (1998); Hu (2001)

Coble et al. (1997)
Caldwell et al. (1998)

Cosmic Variance Problem

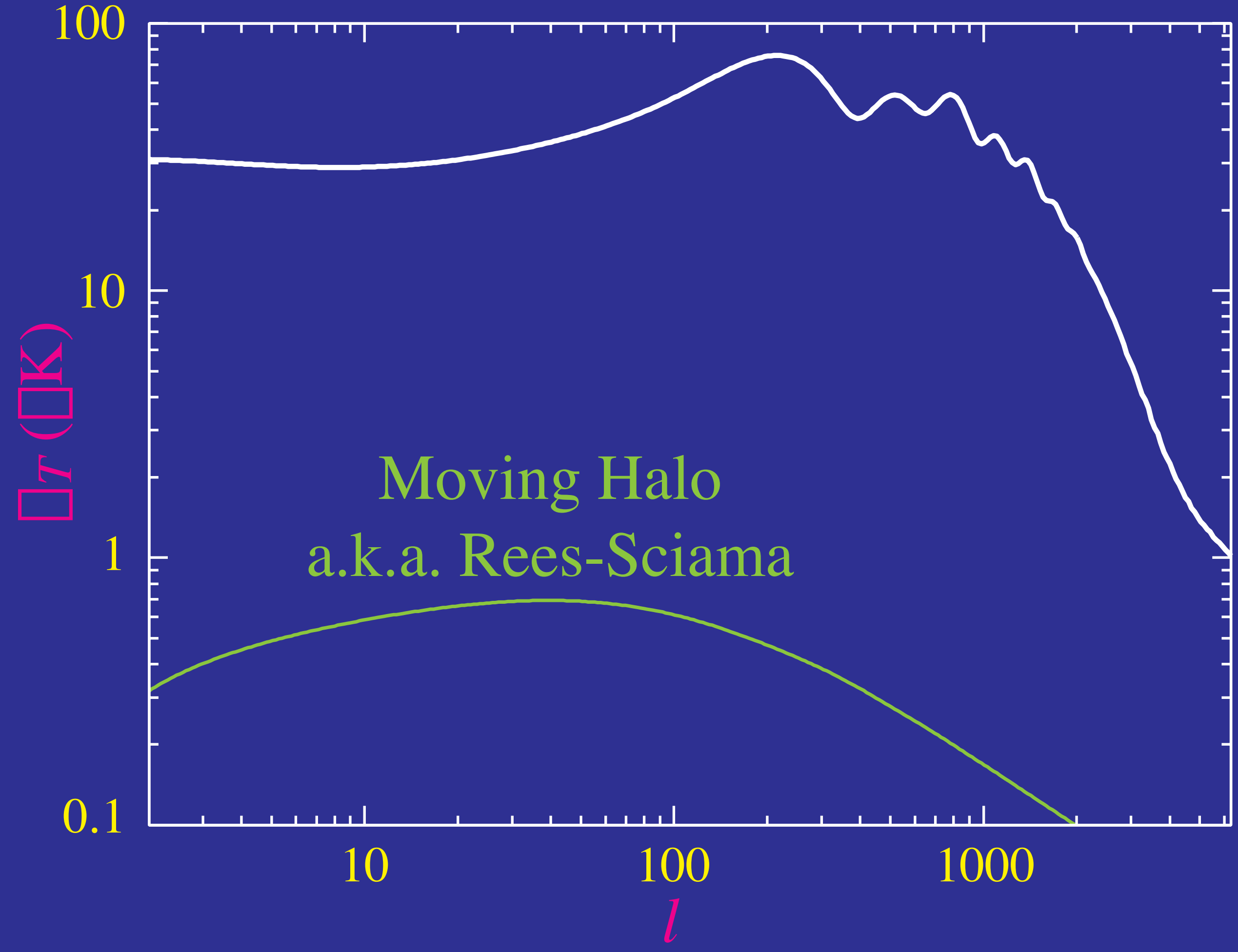
- Power spectrum sampling errors = $[(l+1/2)f_{sky}]^{-1/2}$
- Low multipole effects severely cosmic variance limited



Moving Halo Effect

Moving Halo Effect

- Change in potential due to halo moving across the line of sight



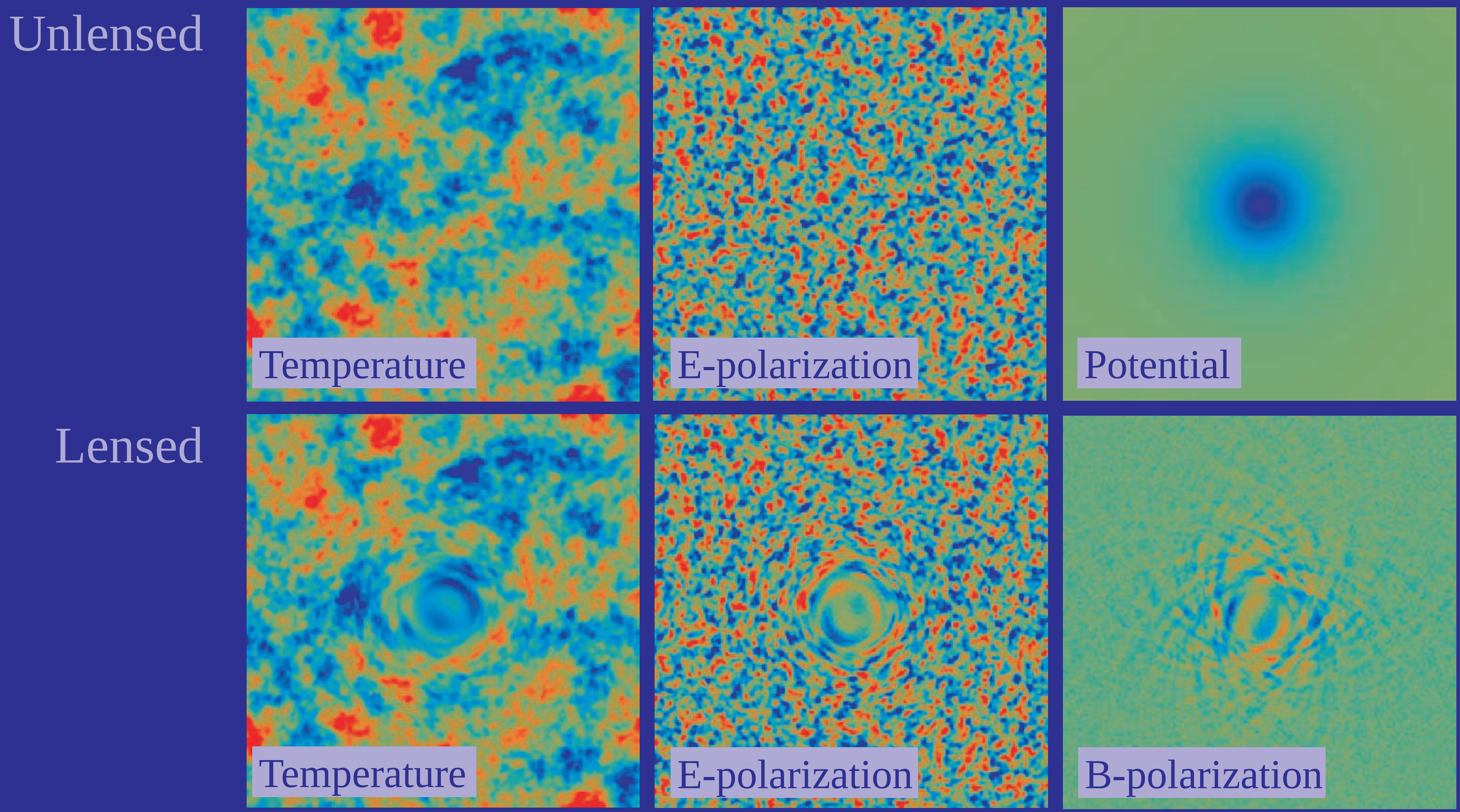
CMB
Temperature & Polarization
Lensing

Lensing of a Gaussian Random Field

- CMB temperature and polarization anisotropies are Gaussian random fields – unlike galaxy weak lensing
- Average over many noisy images – like galaxy weak lensing

Temperature & Polarization

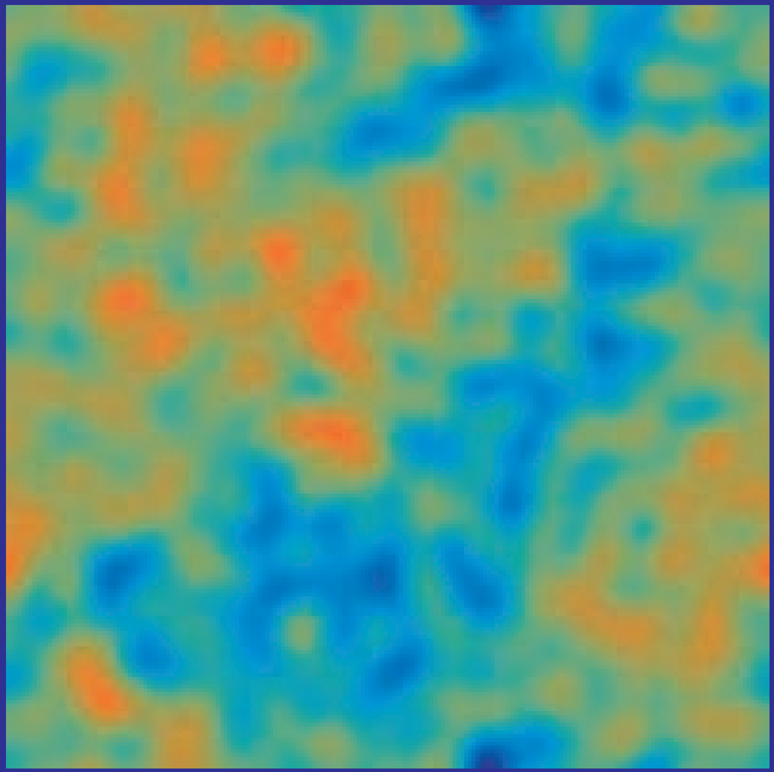
- Mass distribution at large angles and high redshift in in the linear regime (100 sq. deg.)



Hu & Okamoto (2001)

Lensing by a Gaussian Random Field

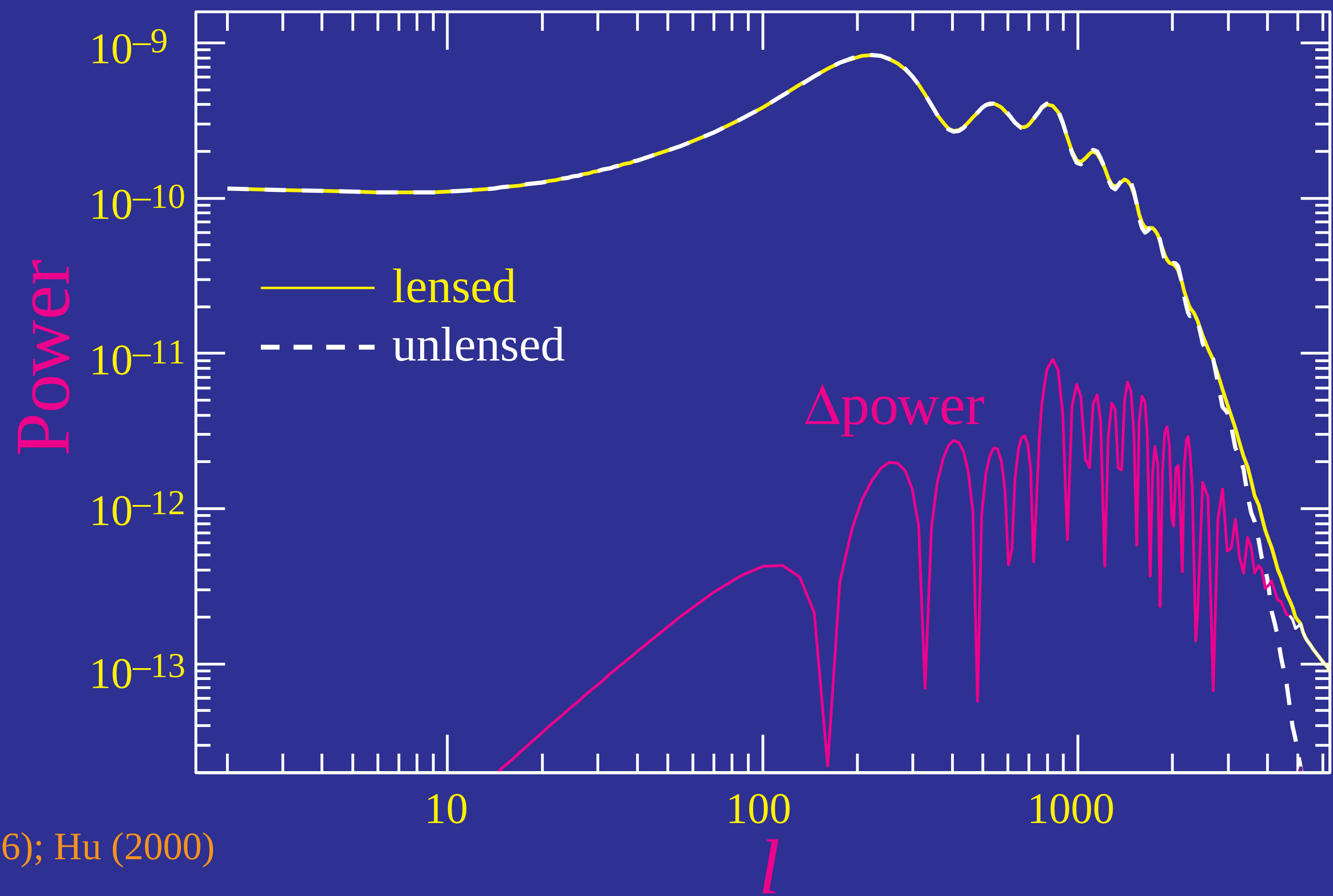
- Mass distribution at large angles and high redshift in in the linear regime
- Projected mass distribution (low pass filtered reflecting deflection angles): 1000 sq. deg



rms deflection
2.6'
deflection coherence
10°

Lensing in the Power Spectrum

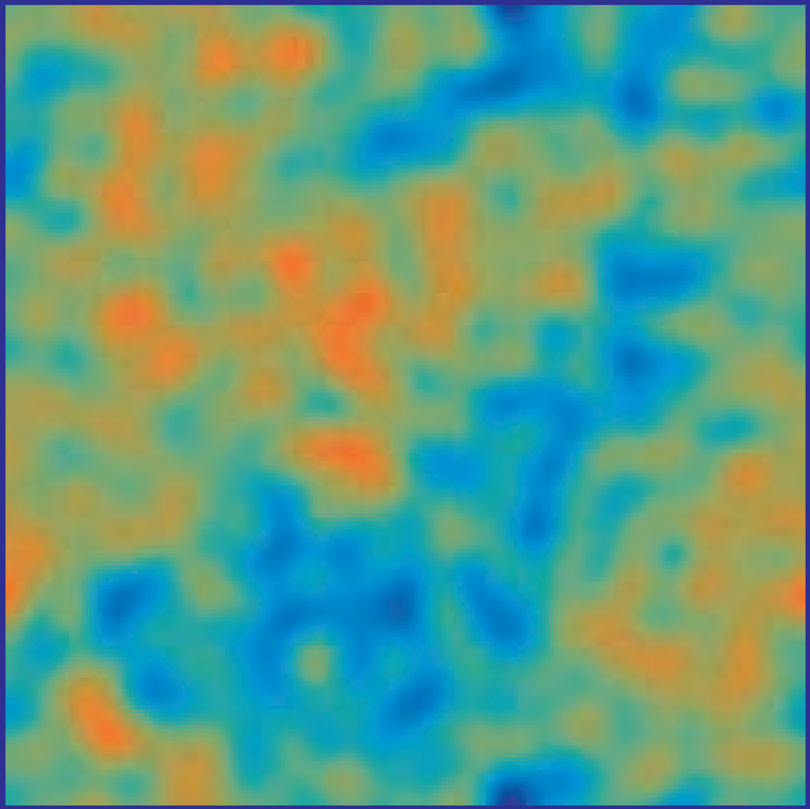
- Lensing smooths the power spectrum with a width $\Delta l \sim 60$
- Convolution with specific kernel: higher order correlations between multipole moments – not apparent in power



Seljak (1996); Hu (2000)

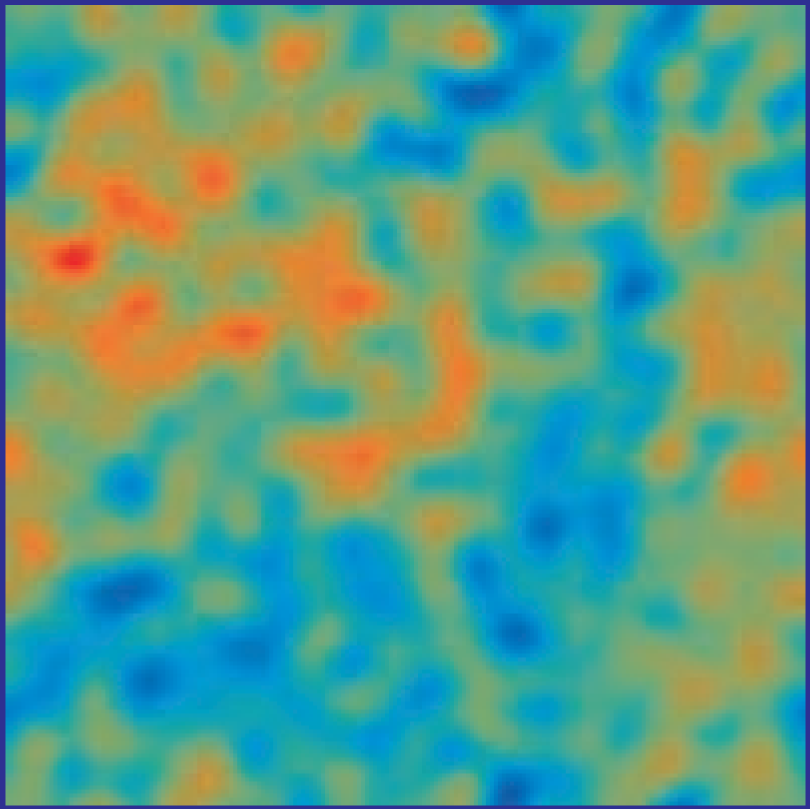
Quadratic Reconstruction

- Matched filter (minimum variance) averaging over pairs of multipole moments
- Real space: divergence of a temperature-weighted gradient



original

potential map (1000sq. deg)



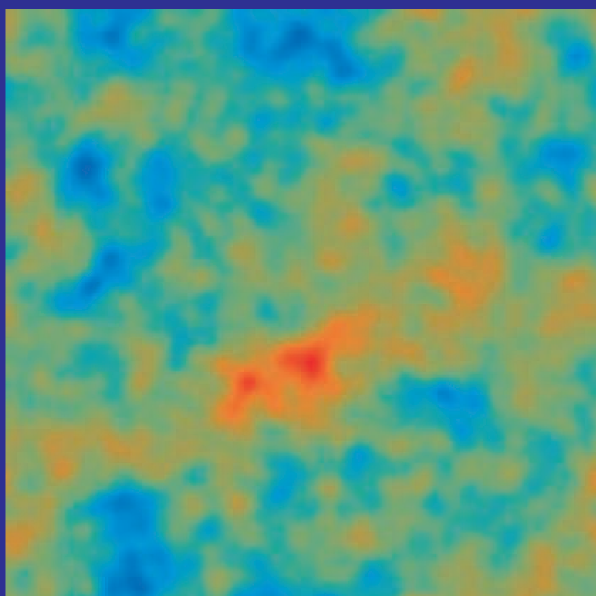
reconstructed

1.5' beam; 27μK-arcmin noise

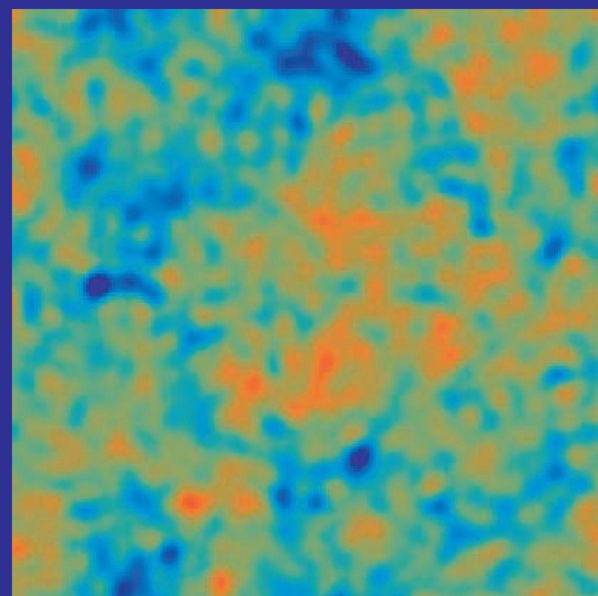
Hu (2001)

Ultimate (Cosmic Variance) Limit

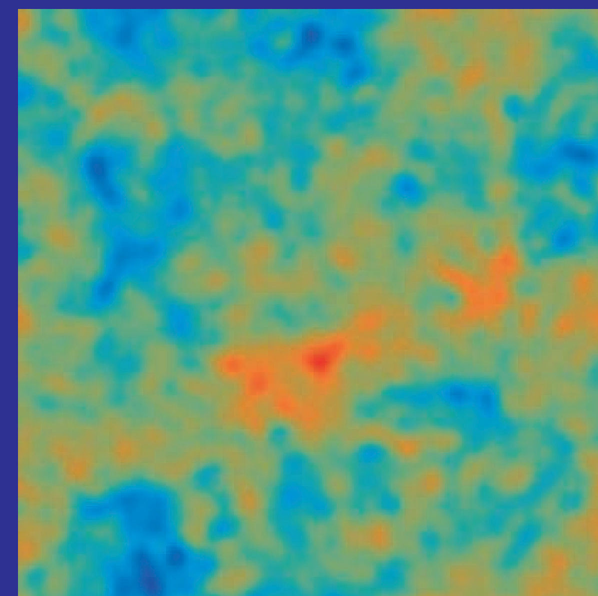
- Cosmic variance of CMB fields sets ultimate limit
- Polarization allows mapping to finer scales (~10')



mass



temp. reconstruction



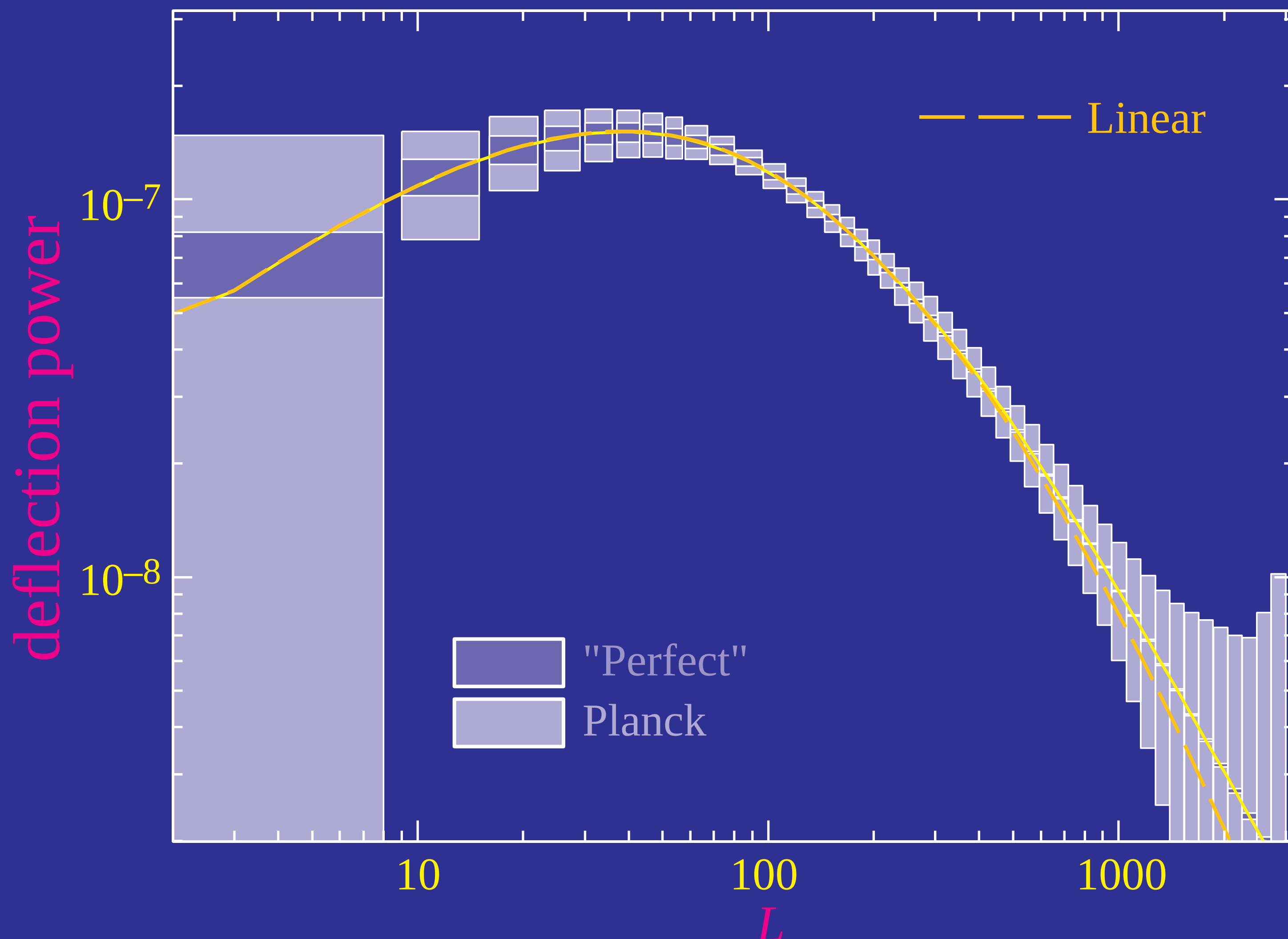
EB pol. reconstruction

100 sq. deg; 4' beam; 1μK-arcmin

Hu & Okamoto (2001)

Matter Power Spectrum

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

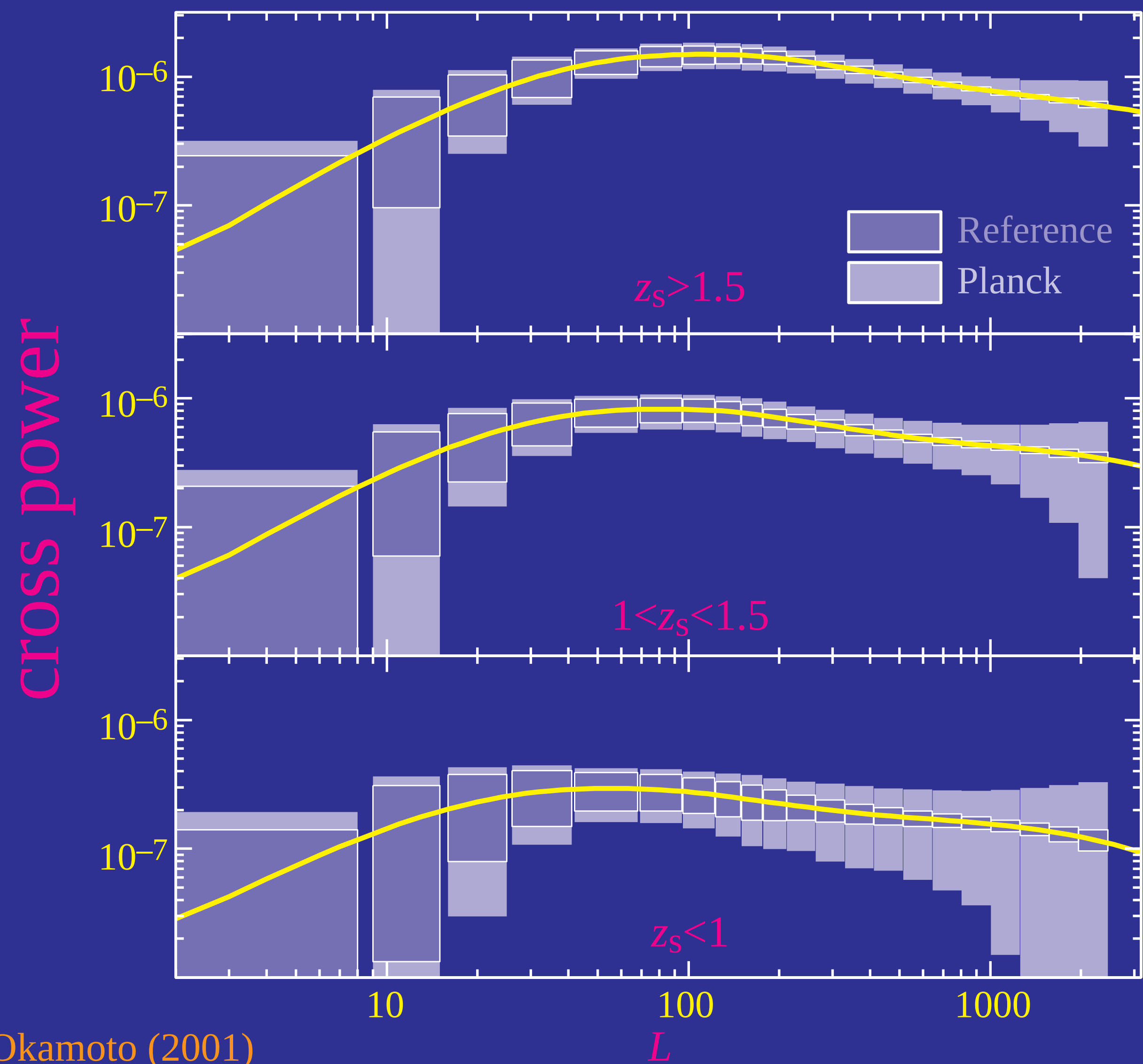


Hu & Okamoto (2001)

σ(*w*)~0.06; 0.14

Tomography & Growth Rate

- Cross correlation with cosmic shear – mass tomography anchor in the decelerating regime

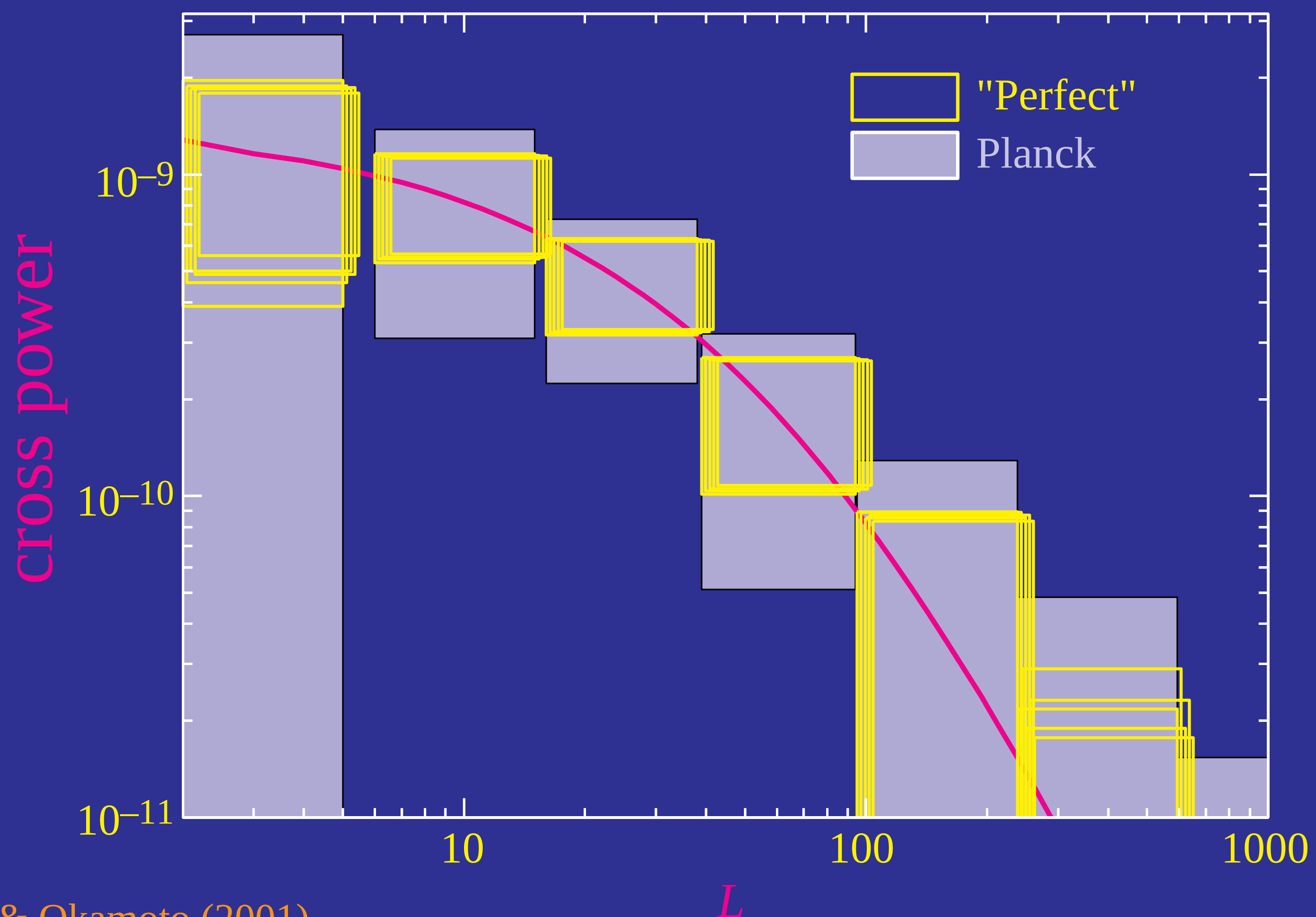


1000 sq. deg.

Hu (2001); Hu & Okamoto (2001)

Cross Correlation with Temperature

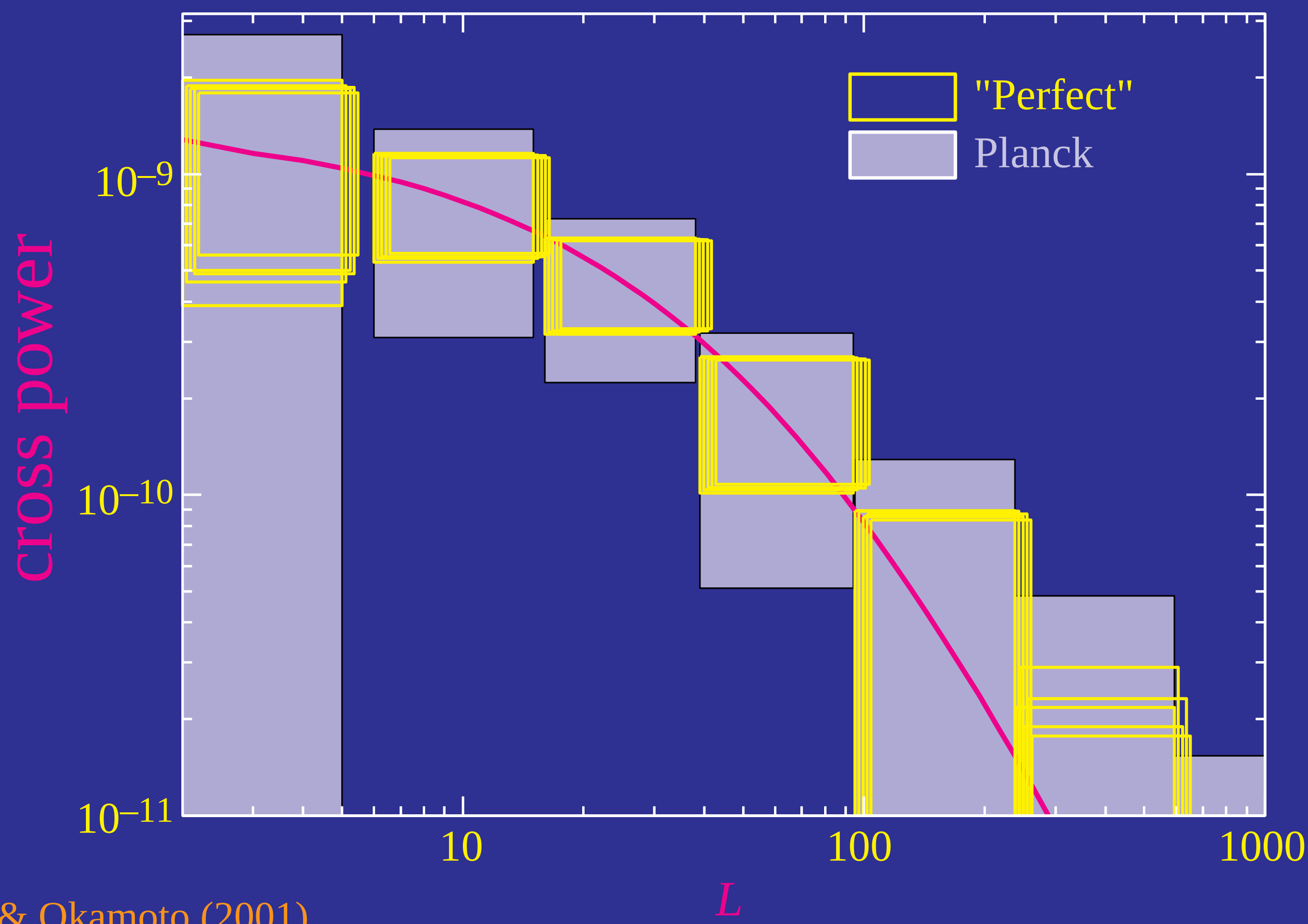
- Any correlation is a direct detection of a smooth energy density component through the ISW effect
- 5 nearly independent measures in temperature & polarization



Hu (2001); Hu & Okamoto (2001)

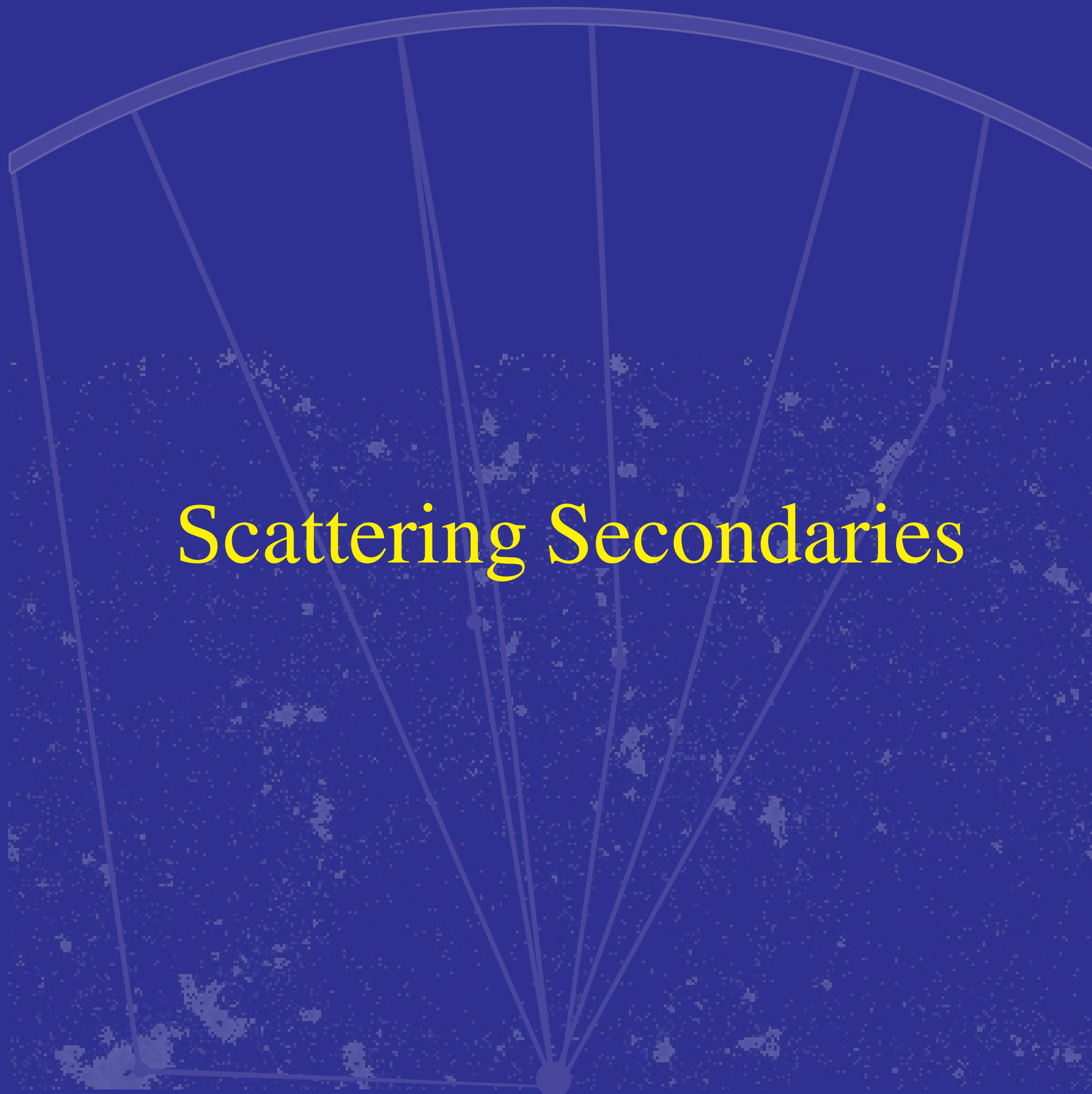
Cross Correlation with Temperature

- Any correlation is a direct detection of a smooth energy density component through the ISW effect
- Show dark energy smooth >5-6 Gpc scale, test quintesence

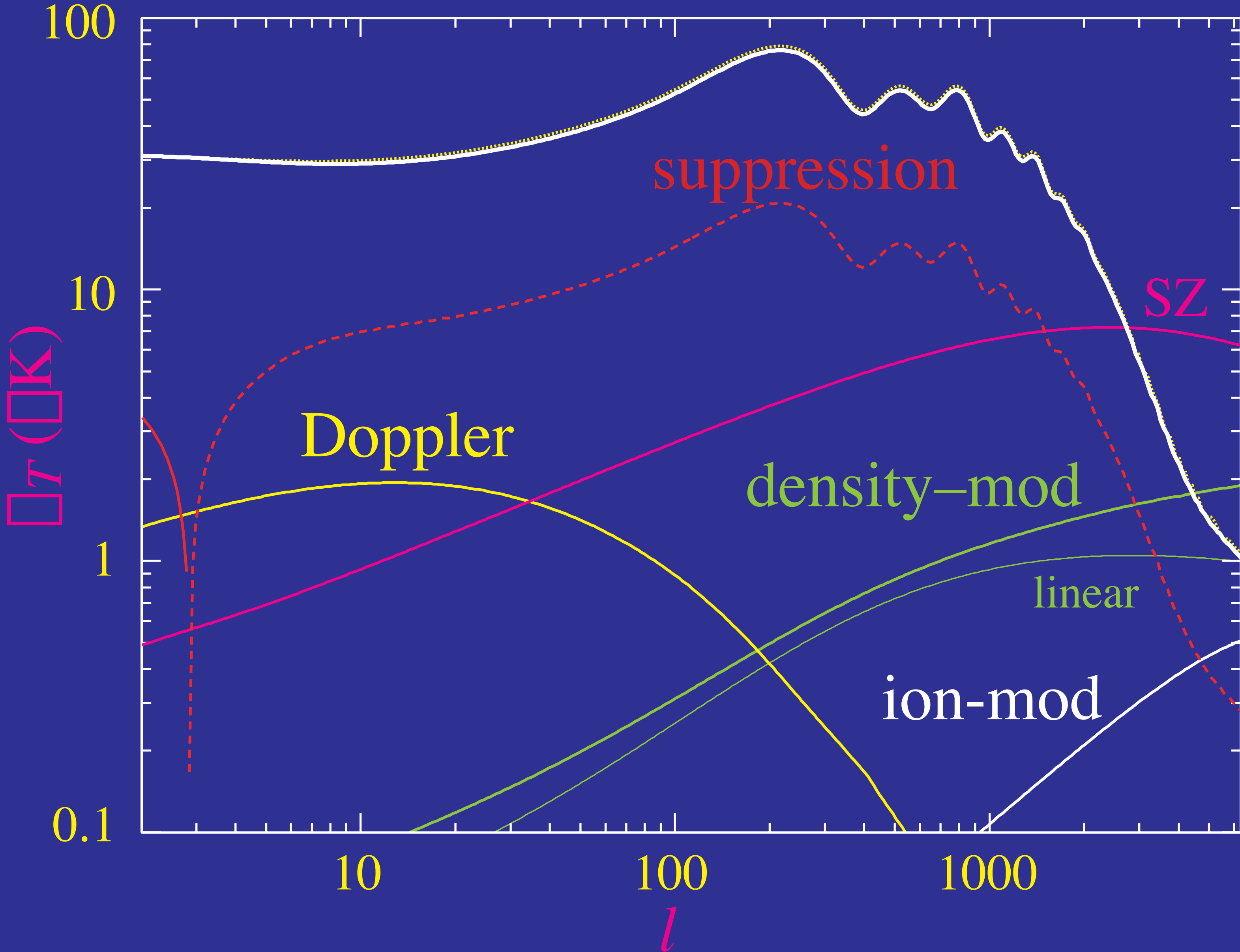


Hu (2001); Hu & Okamoto (2001)

Scattering Secondaries

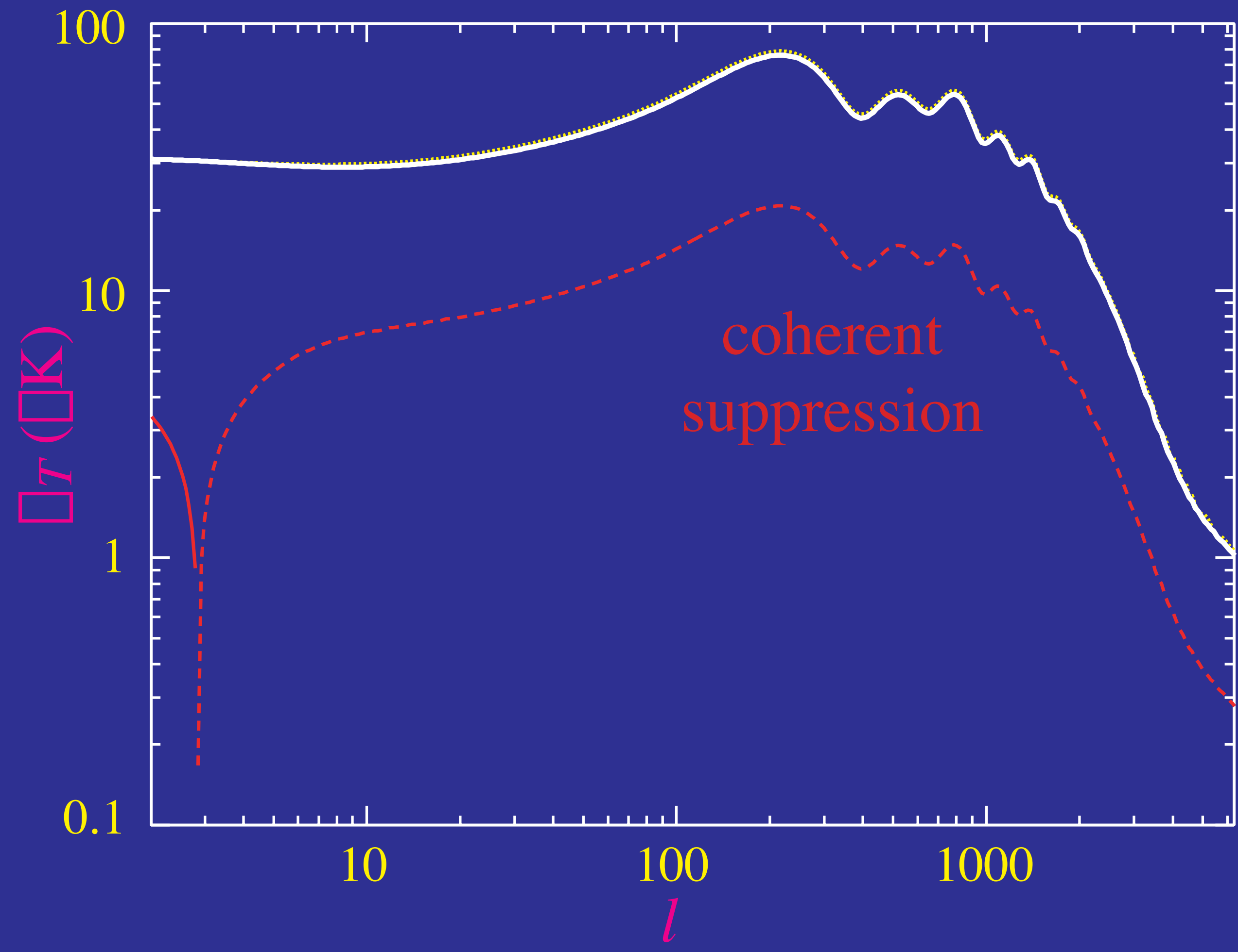


Scattering Secondaries



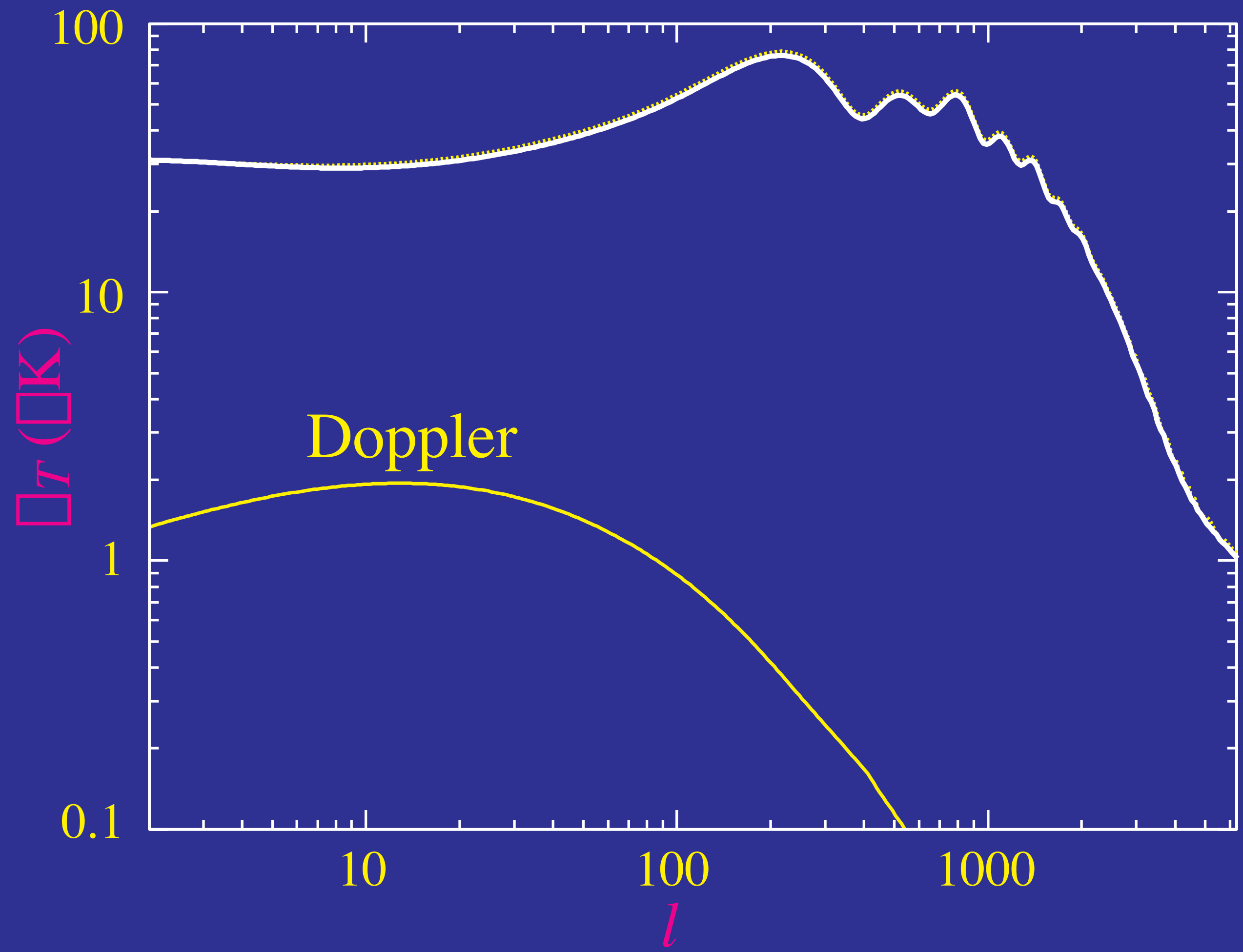
Reionization Suppression

- Main effect of reionization is a suppression of anisotropies
- Rescattering isotropizes photons: $e^{-\tau}$ in amplitude

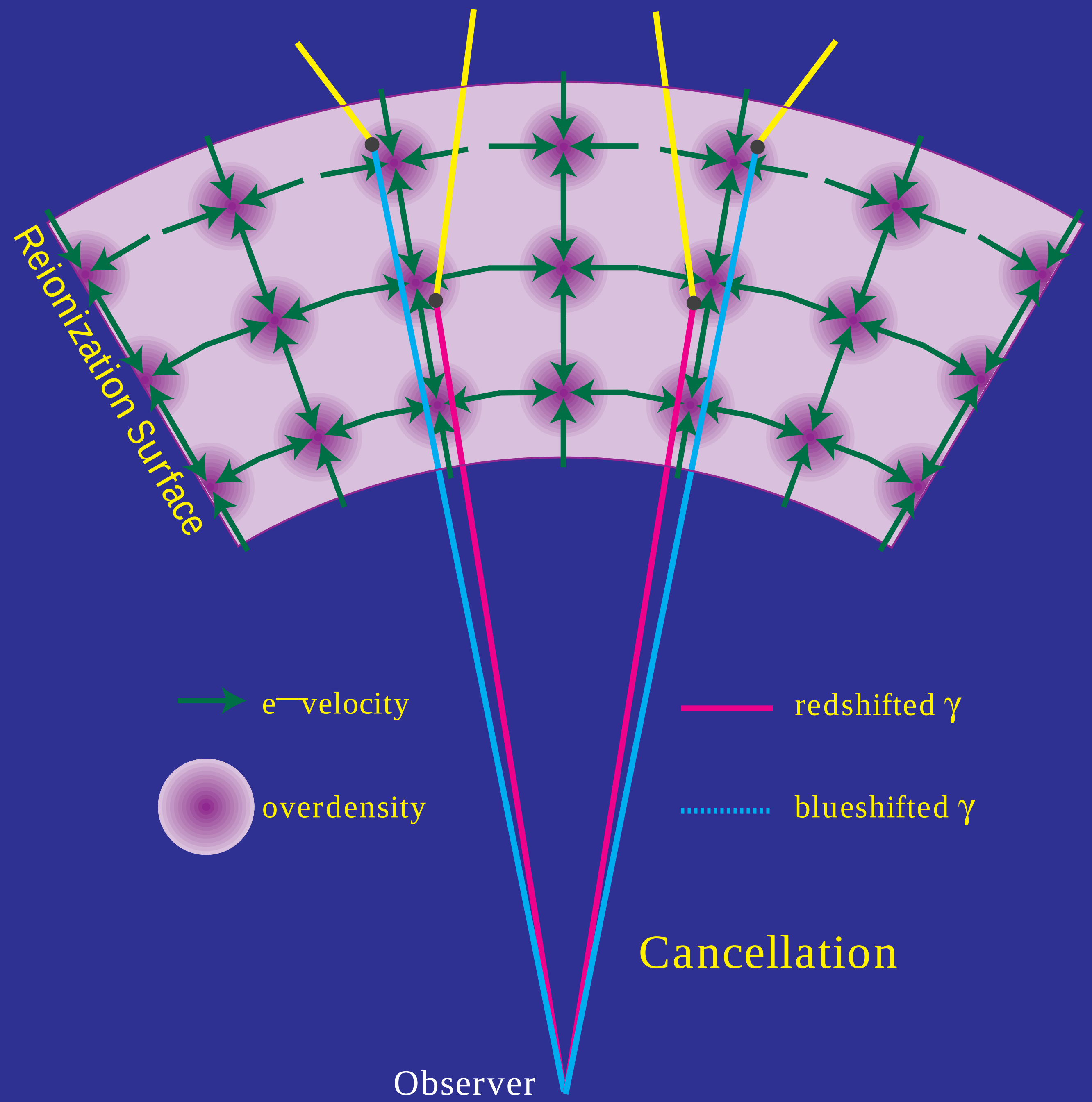


Doppler Effect

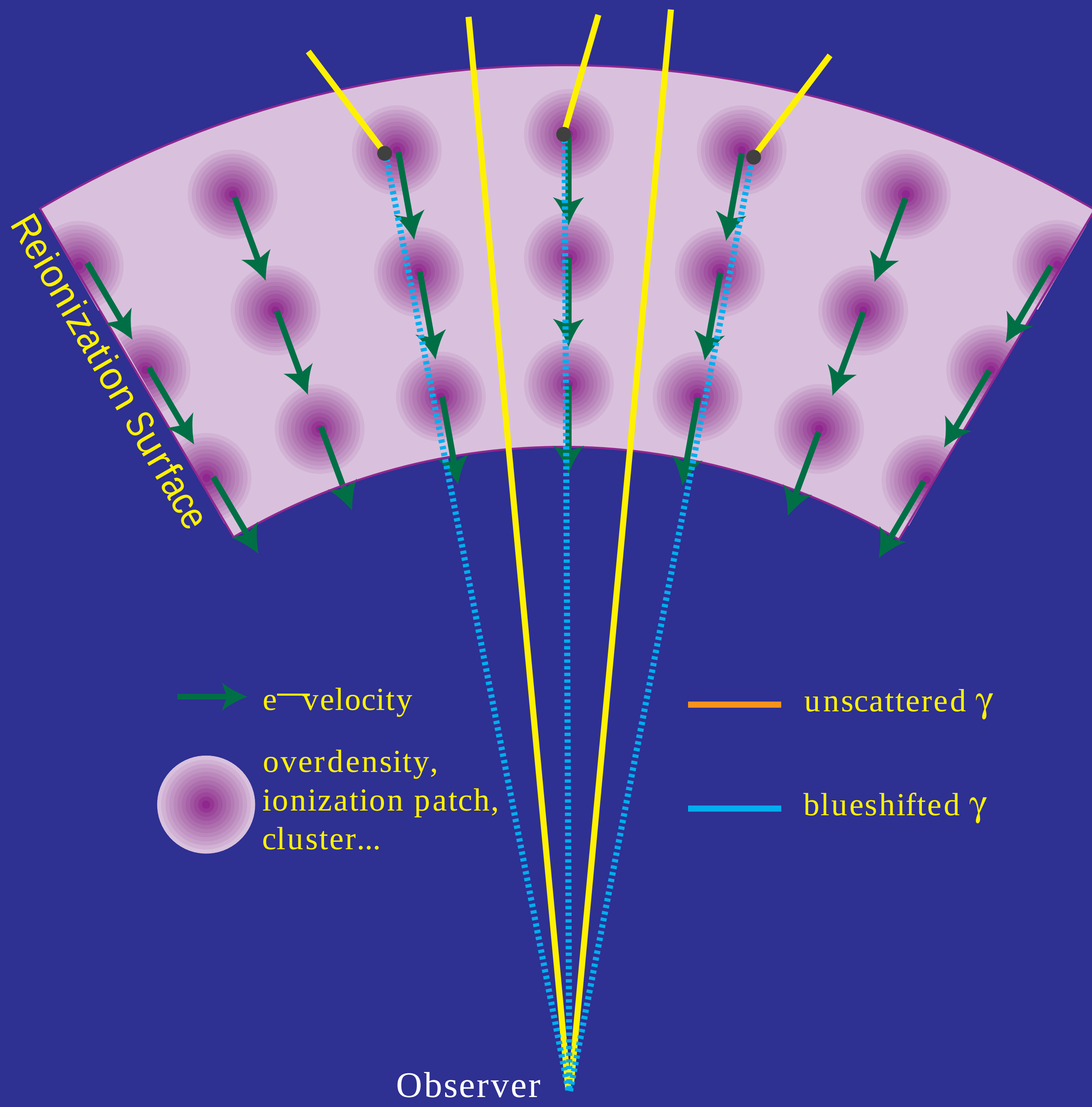
- Naively: □ ~ few 10^{-2}, $v \sim 10^{-3}$
- Implies: $□_T \sim T\, v\, □ \sim$ few 30□K – too large!



Cancellation of the Linear Effect

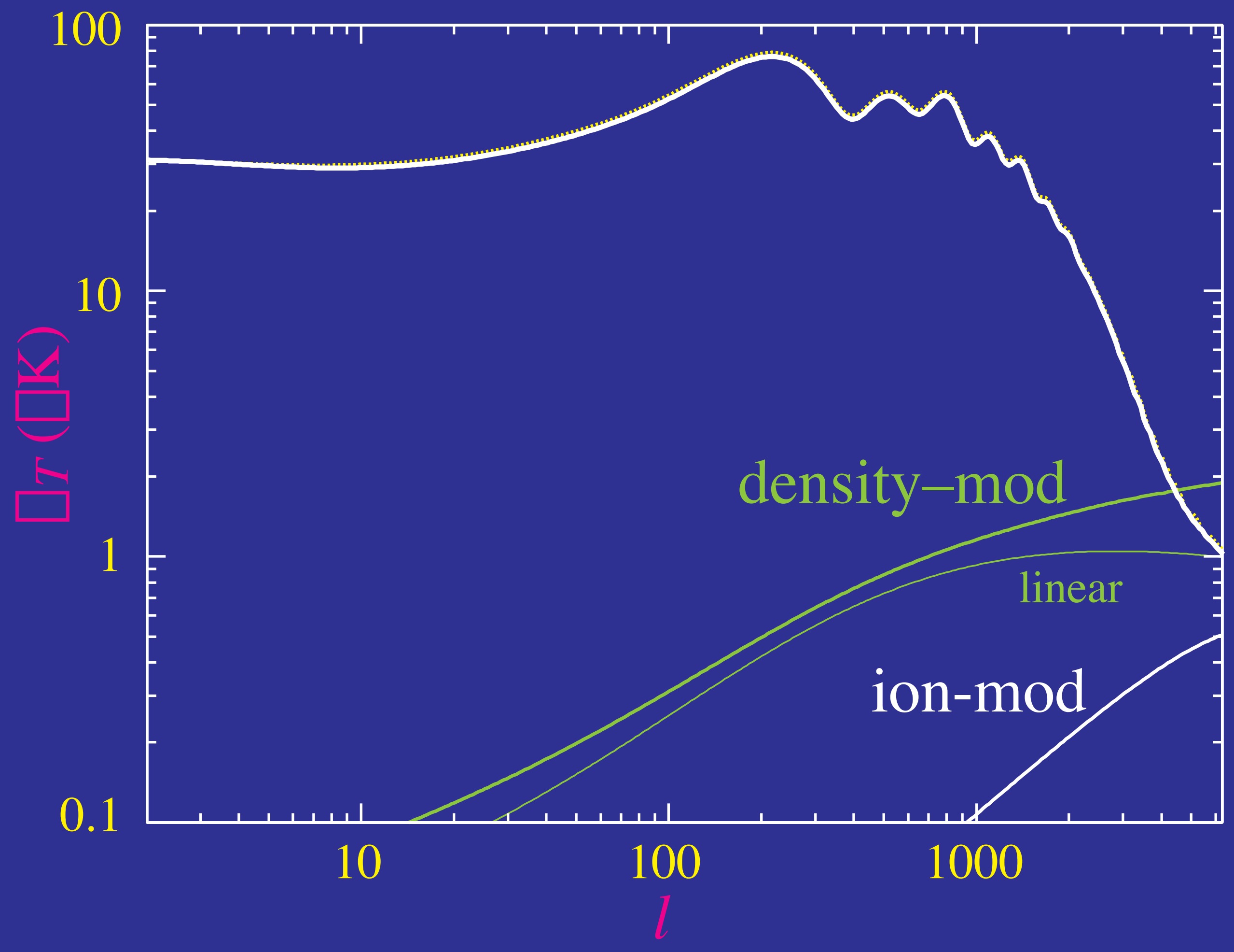


Modulated Doppler Effect

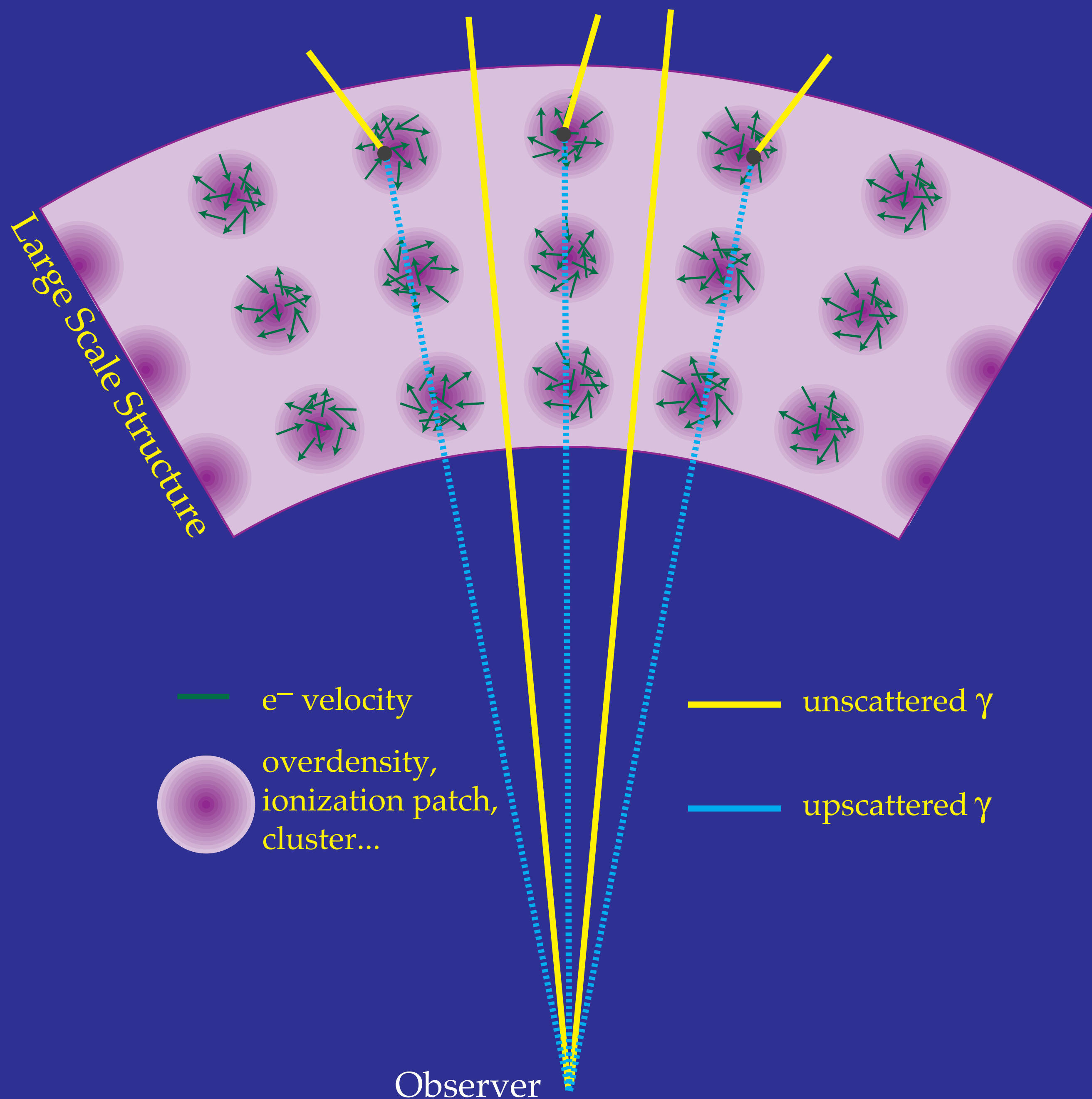


Modulated Doppler Effect

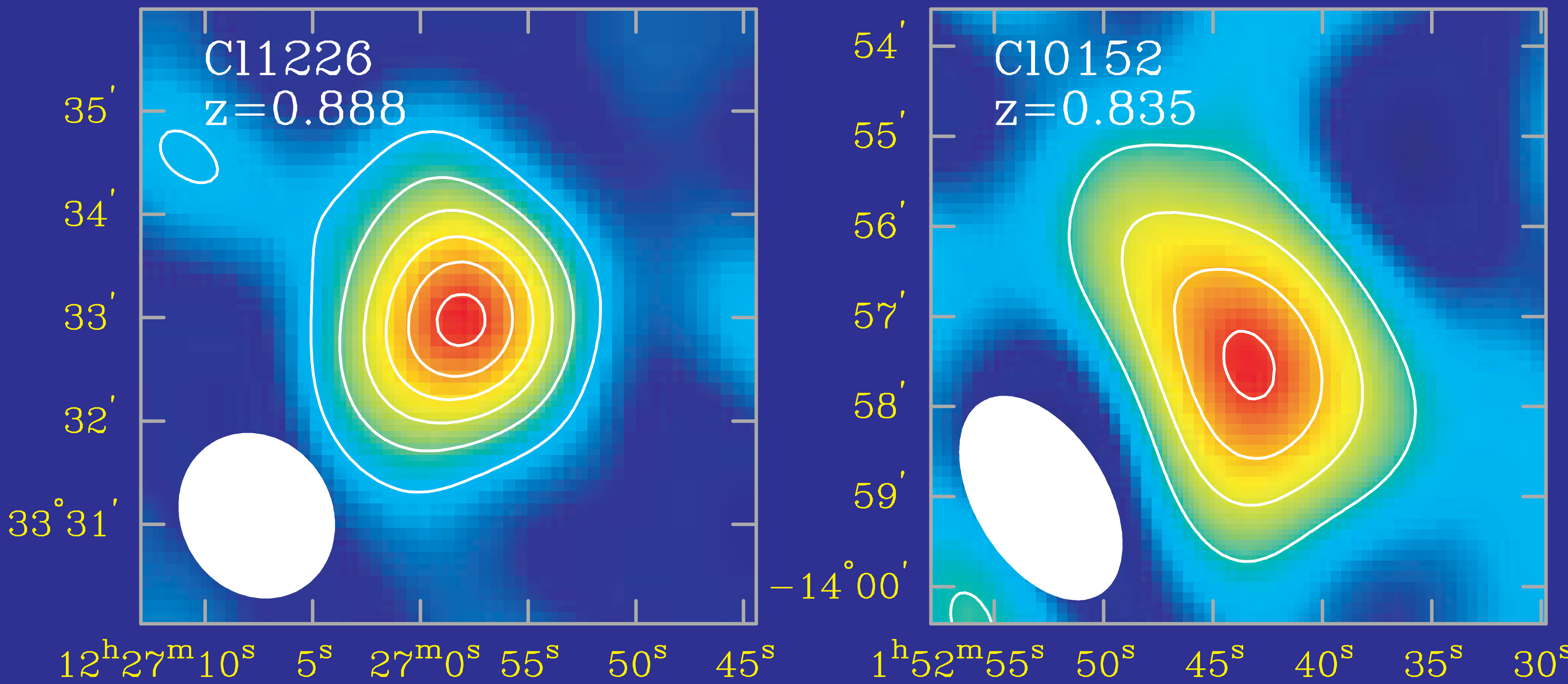
- Optical depth modulated by density or ionization at small angles
- Linear density = Vishniac; Cluster density = Kinetic SZ
Ionization = Inhomogeneous (patchy) reionization



Thermal SZ Effect



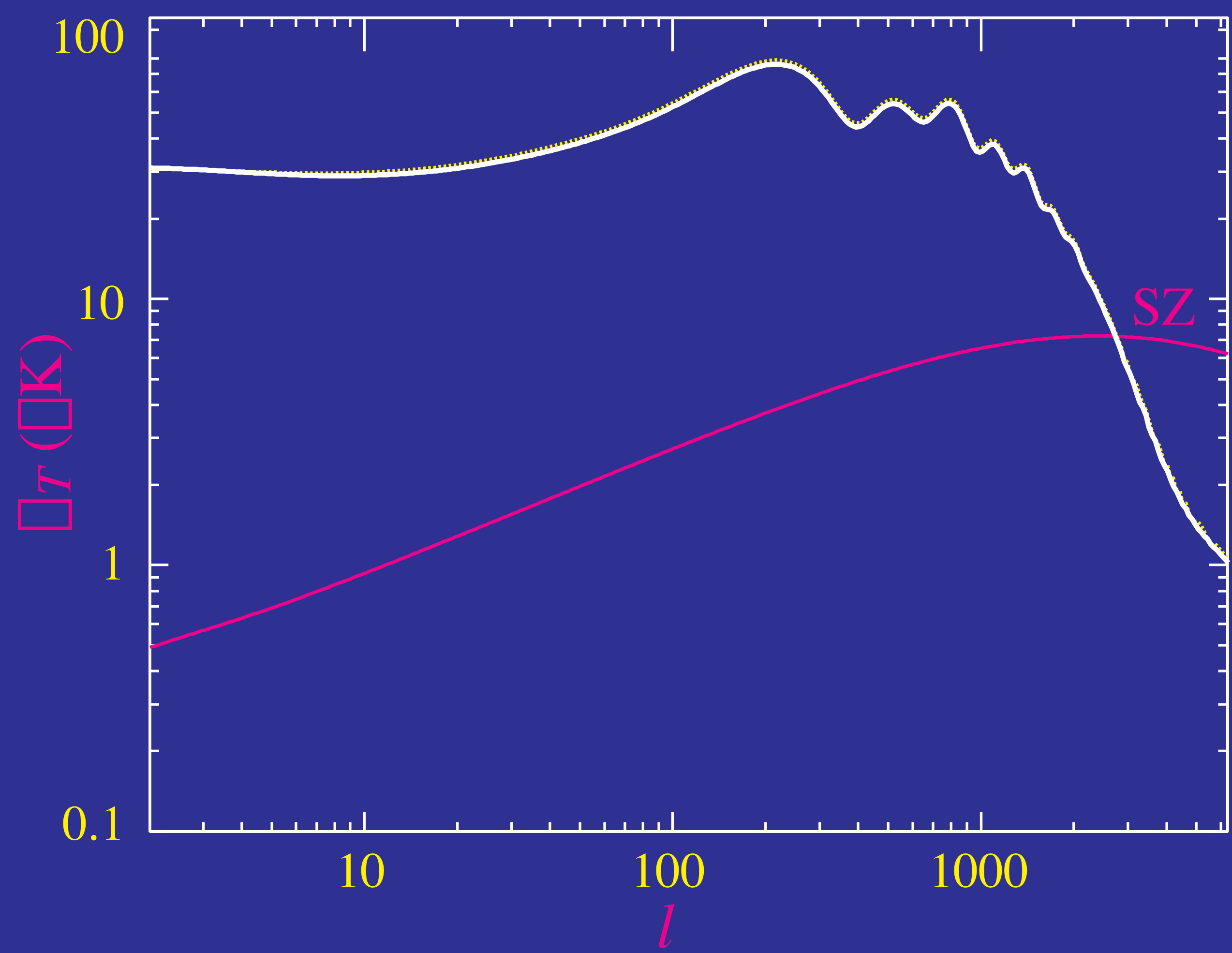
Clusters Seen in SZ



Carlstrom et al. (2001)

Thermal SZ Effect

- Second order Doppler effect escapes cancellation
- Velocities: thermal velocities in a hot cluster (1-10keV)
- Dominant source of arcminute anisotropies – turns over as clusters are resolved

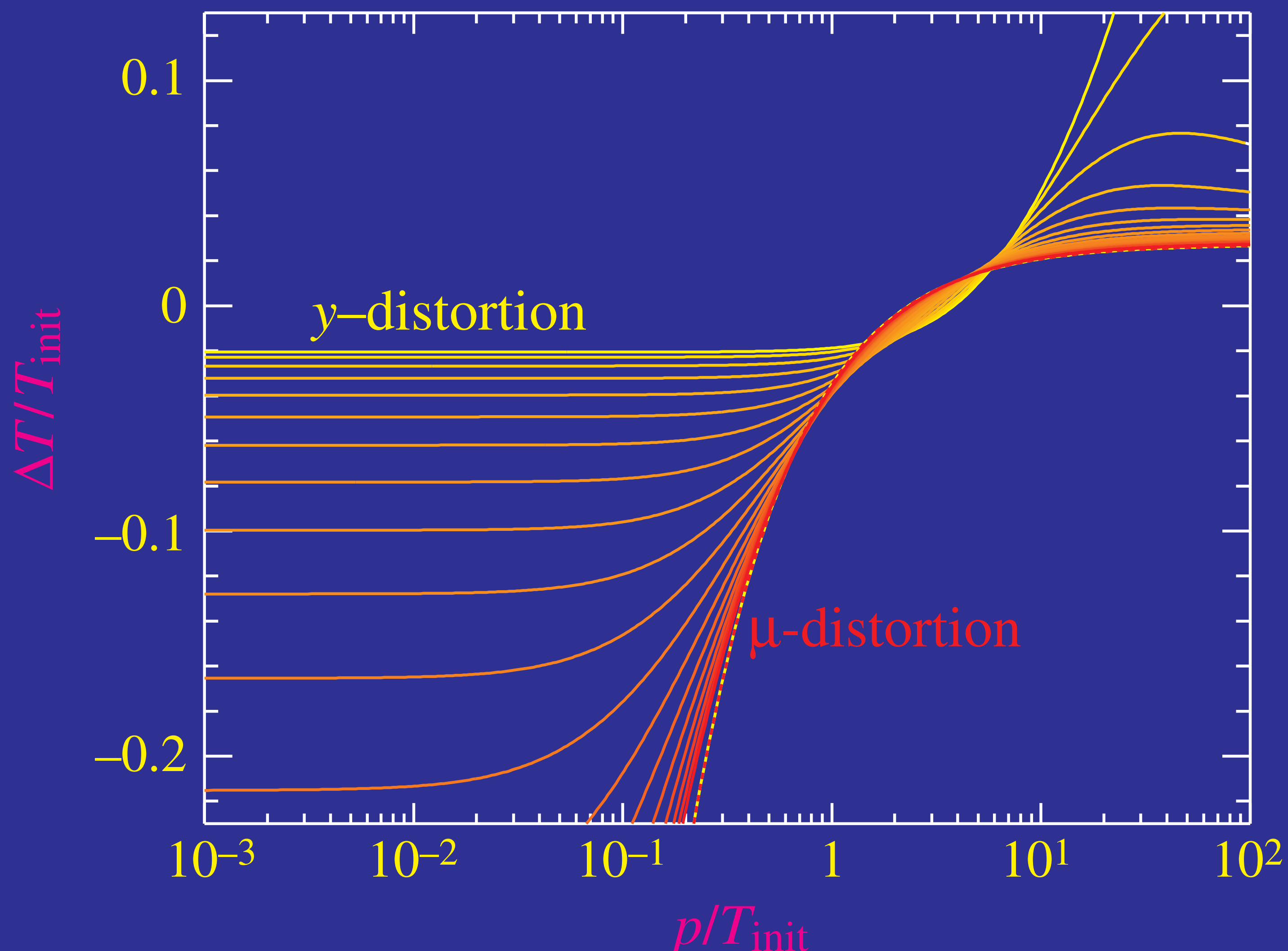


Amplitude of Fluctuations

Dark Energy and SZ Effect

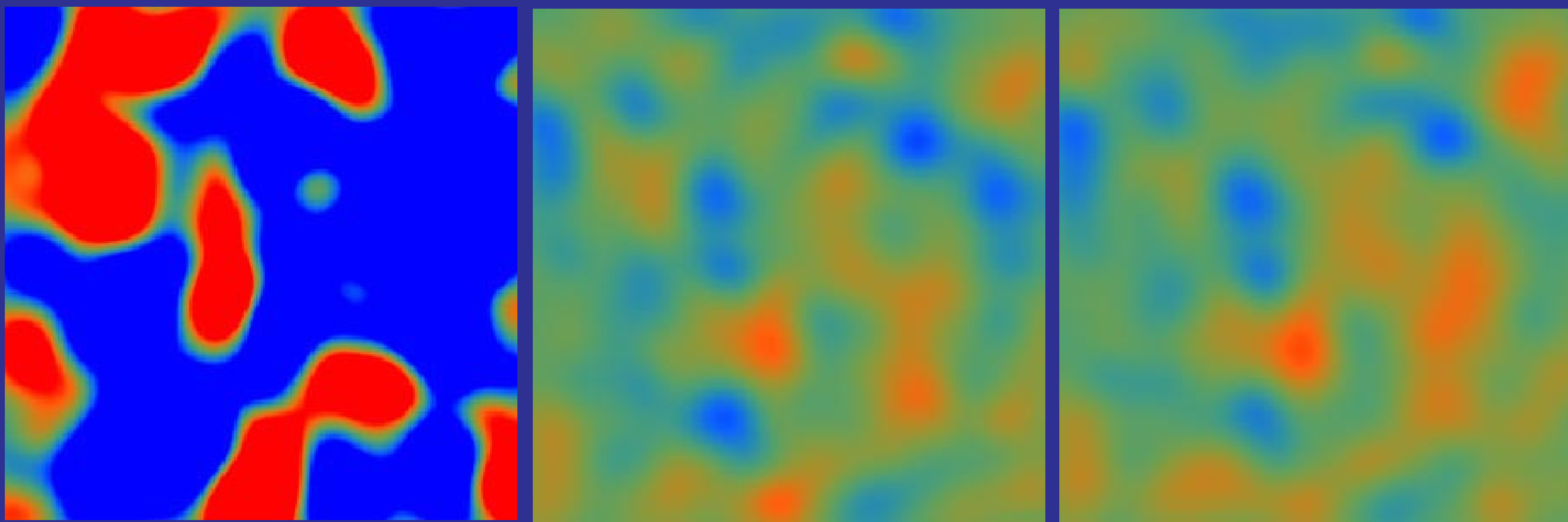
Spectral Distortion

- Compton upscattering: *y*–distortion
- Redistribution: μ-distortion



Extracting the SZ Foreground

- Multifrequency extraction of SZ signal in presence of foregrounds
- CMB itself is the primary ‘‘foreground’’
- Planck channels & sensitivity



Rayleigh-Jeans
CMB+Foregrounds

SZ Signal

Cleaned Map

- Toy SZ model: pressure a biased tracer of mass + PM simulations
  6º x 6º smoothed at 20'

Cooray, Hu & Tegmark (1999)

CMB Future

- Primary anisotropies have established a secure cosmological framework
- Three incompletely answered questions:
  (inflationary?) origin of fluctuations
  nature of dark energy
  first objects in the Universe
- Resolution tied to secondary anisotropies

CMB Future

- Primary anisotropies have established a secure cosmological framework
- Three incompletely answered questions:
  (inflationary?) origin of fluctuations
  nature of dark energy
  first objects in the Universe
- Resolution tied to secondary anisotropies
- CMB photons travel through intervening structure in universe
- Gravitational secondaries (ISW, lensing) test dark energy properties
- Scattering secondaries probe reionization and clusters
- Lensing contaminates inflationary B-modes