# Cosmology:
## The effect of cosmological parameters on the angular power spectrum of the Cosmic Microwave Background

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**and**

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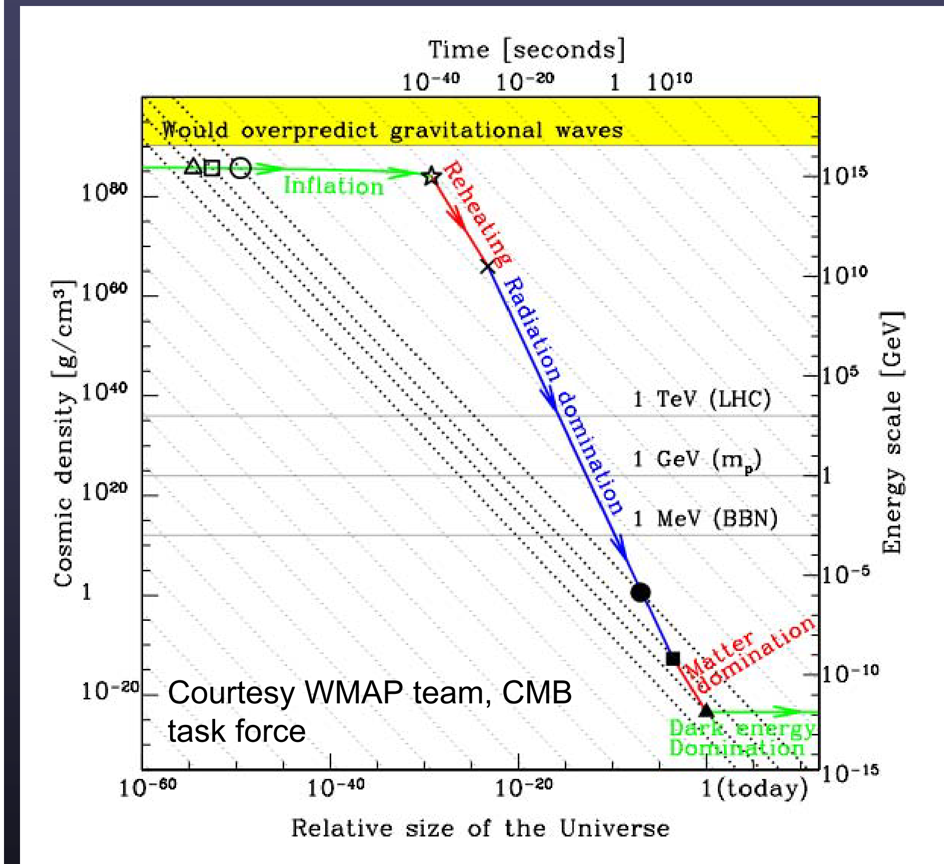
# The Standard Model

Over the past decade we have arrived at a Standard Cosmological Model™



Courtesy WMAP team, CMB task force

## THE PILLARS OF INFLATION

1) super-horizon (>2°) anisotropies
2) acoustic peaks and harmonic pattern (~1°)
3) damping tail (<10')
4) Gaussianity
5) secondary anisotropies
6) polarization
7) gravity waves

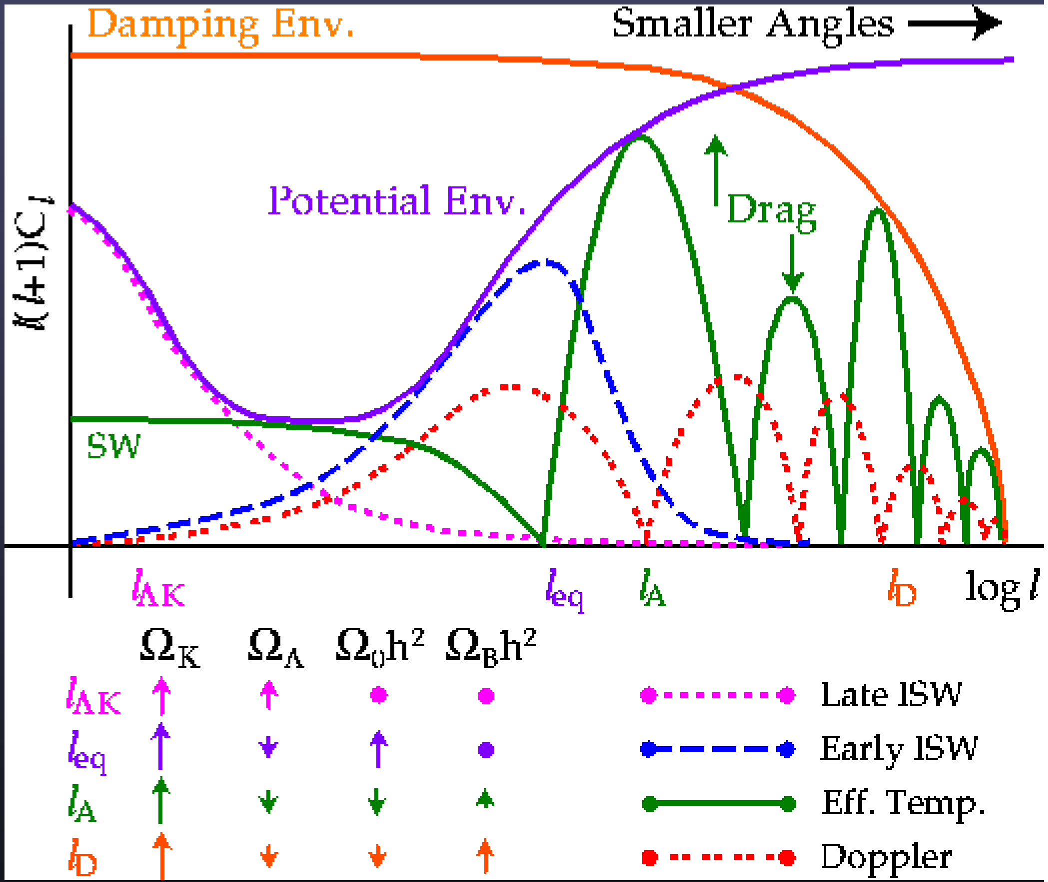
But … to test this we need to measure a signal which is $3\times10^{7}$ times weaker than the typical noise!

The (scalar) cosmological parameters:

| $\Omega_k$ | $\Omega_b$ | $\Omega_{cdm}$ | $n_s$ | $\Omega_\Lambda$ | $\Omega_m$ | h | $\tau$ |
|---|---|---|---|---|---|---|---|
| geometry of the universe | baryonic fraction protons, neutrons | cold dark matter not protons and neutrons | primordial fluctuation spectrum | dark energy negative press-ure of space | matter fraction | Hubble Constant size & age of the universe | optical depth to last scatt-ering of cmb |

# The Angular Power Spectrum

- The CMB angular power spectrum is the sum of many individual physical effects
  - acoustic oscillations
  - (static) variations in potential (Sachs-Wolfe Effect)
  - baryon loading of oscillations
  - photon drag and damping
  - moving scatterers (Doppler)
  - time-varying gravitational potentials (ISW)
  - delayed recombination
  - late reionization

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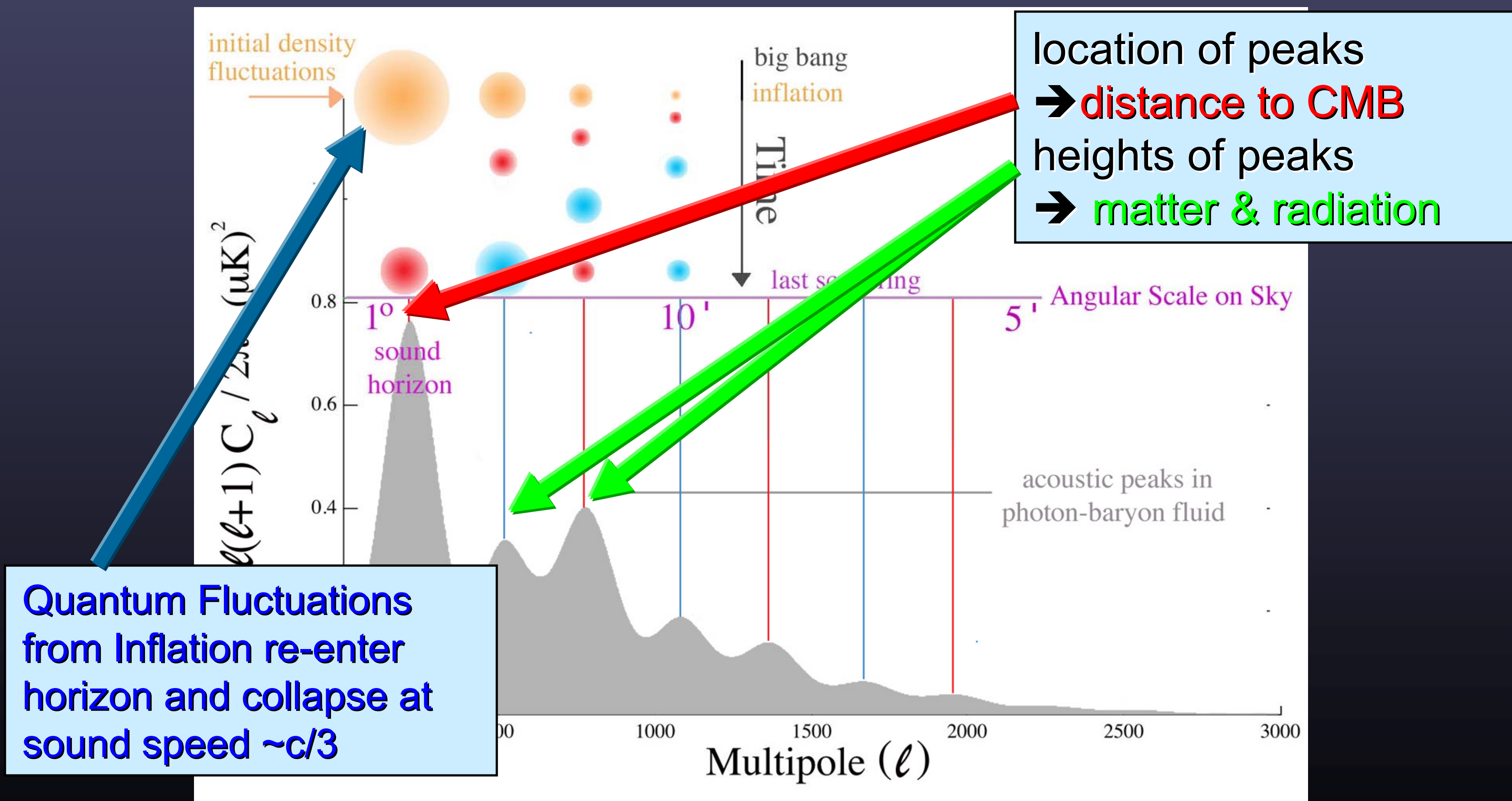
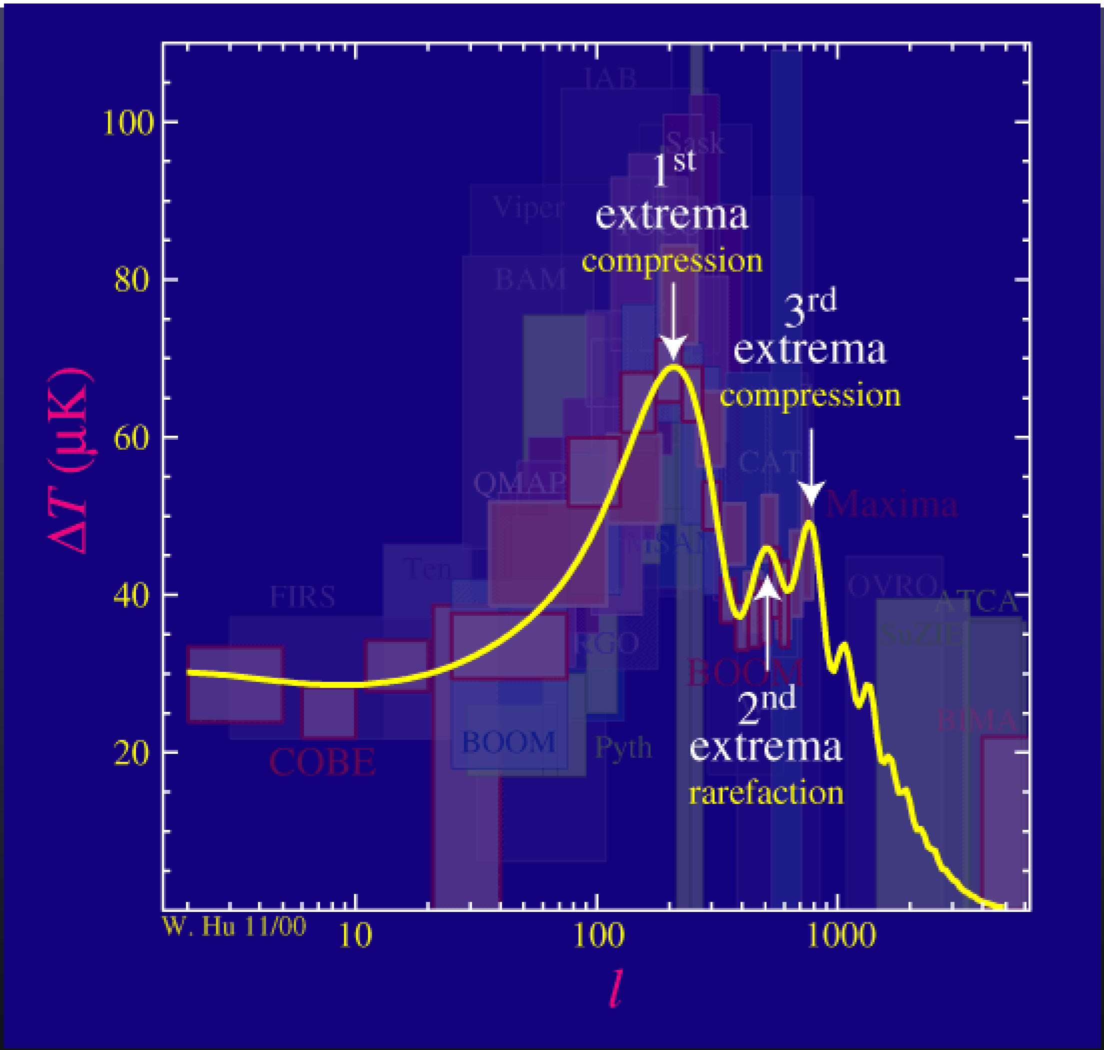
# CMB Acoustic Peaks

- Compression driven by gravity, resisted by radiation
  - ≈ seismic waves in the cosmic photosphere: $\cos(kc_s\eta)$



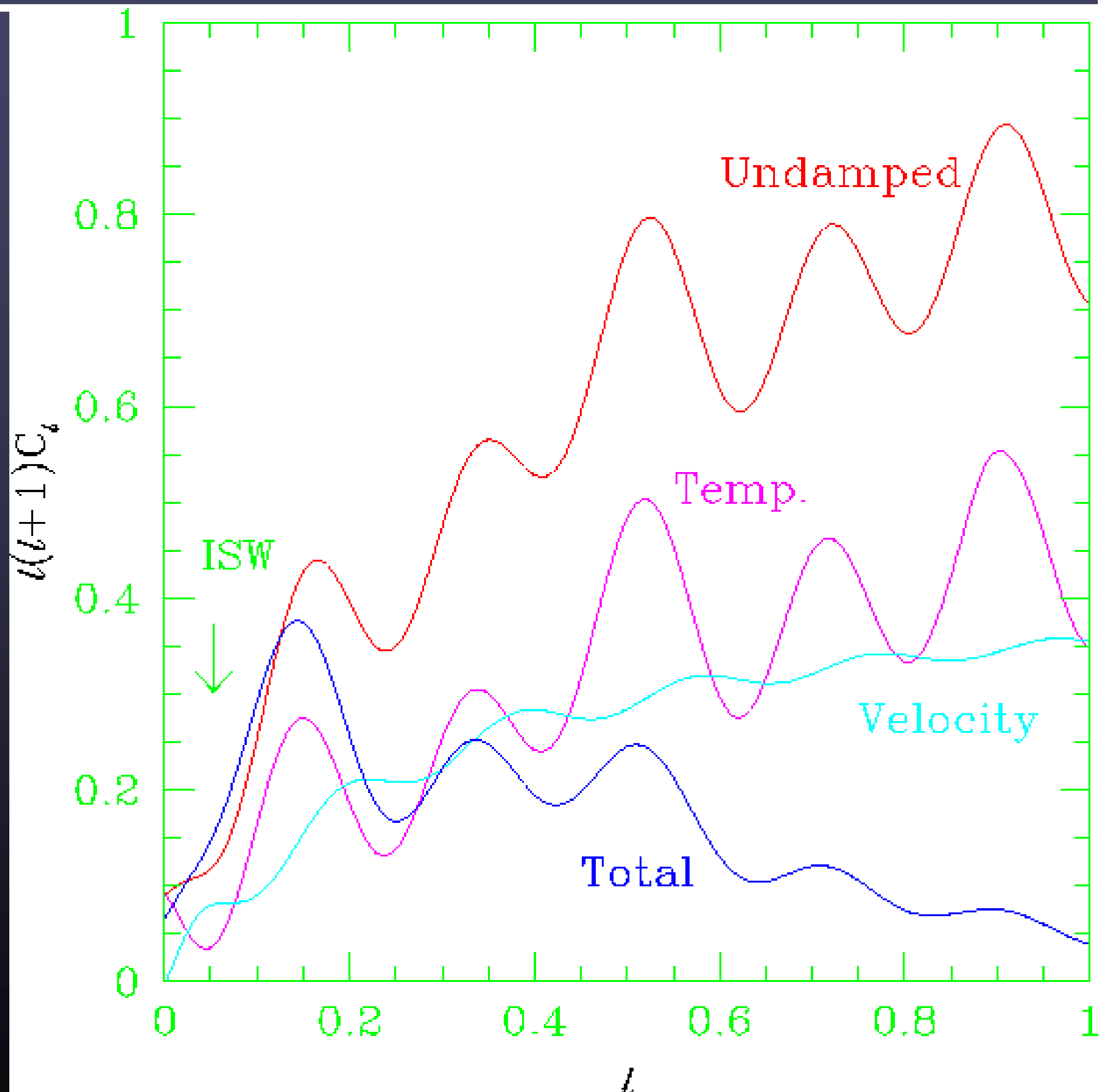
# CMB Acoustic Overtones



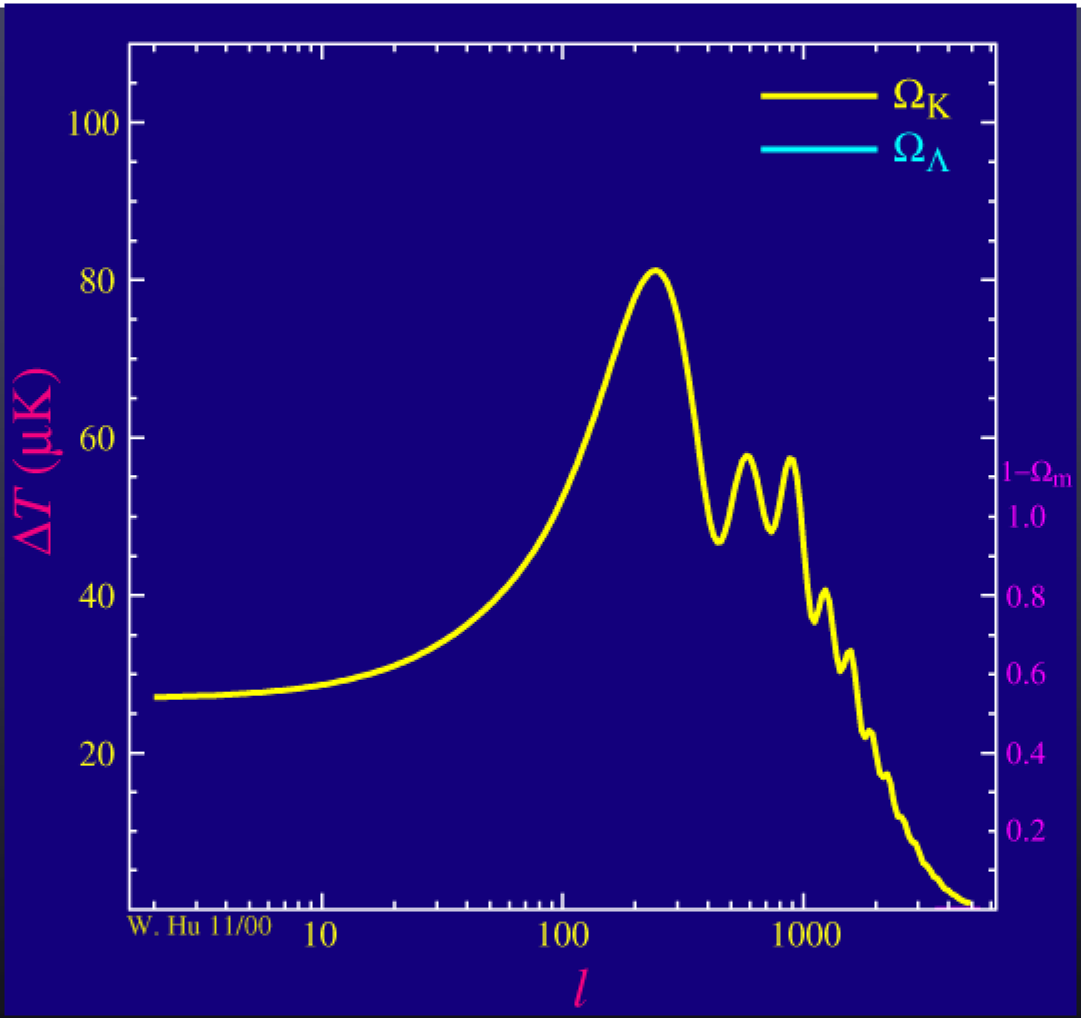

- If we choose to follow a crest (overdensity) after horizon entry, the first acoustic peak is its first compression…

# Doppler Effect

- Due to electron velocities
  - dipole at last scattering
- Out of phase with density fluctuations
  - 90° phase shift
  - $\sin(kc_s\eta)$
- Same size as potential effect
  - but decorrelated by projection onto sky
  - more important in reionized Universe and in polarization!



# Peaks and Curvature




Changing distance to $z$ =1100 shifts peak pattern

- Location and height of acoustic peaks
  - determine values of cosmological parameters
- Relevant parameters
  - curvature of Universe (e.g. open, flat, closed)
  - dark energy (e.g. cosmological constant)
  - amount of baryons (e.g. electrons & nucleons)
  - amount of matter (e.g. dark matter)

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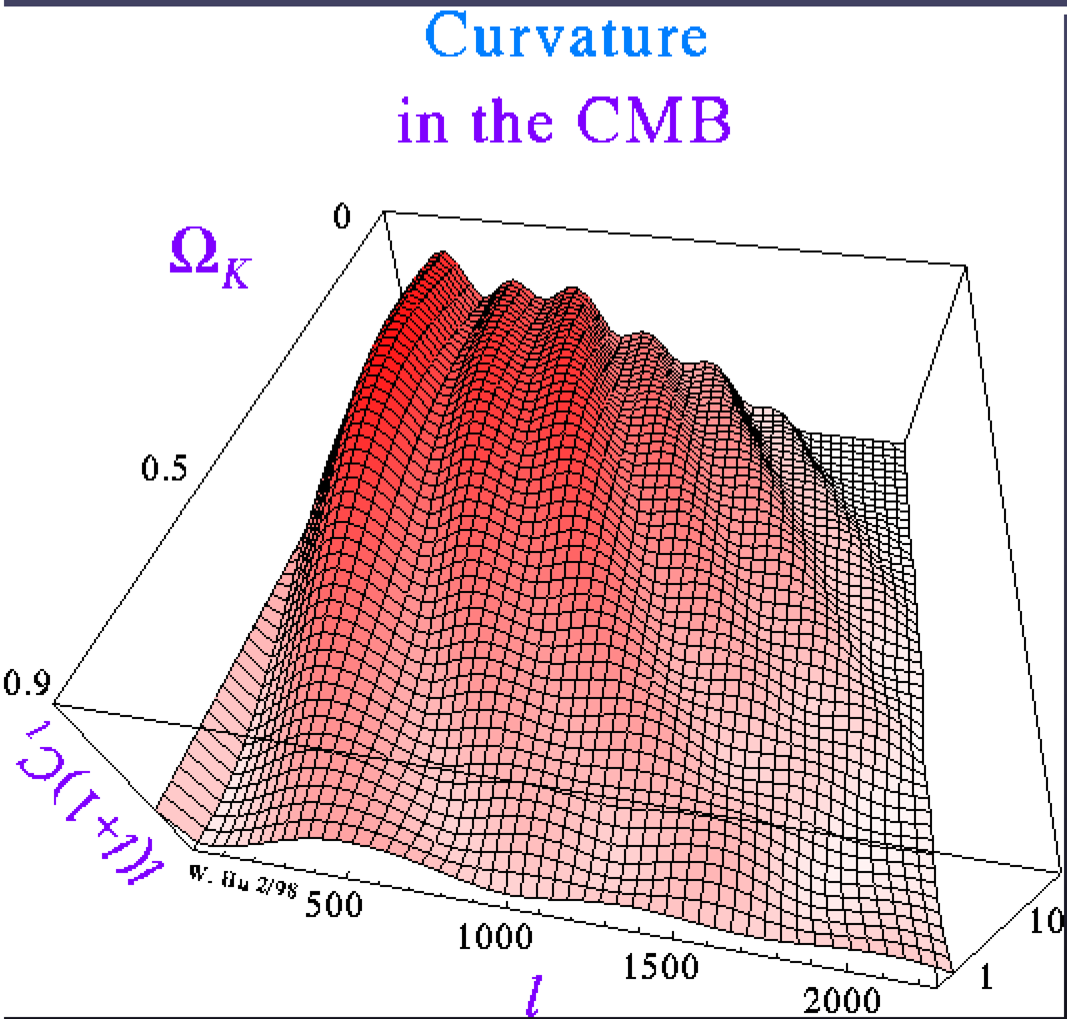


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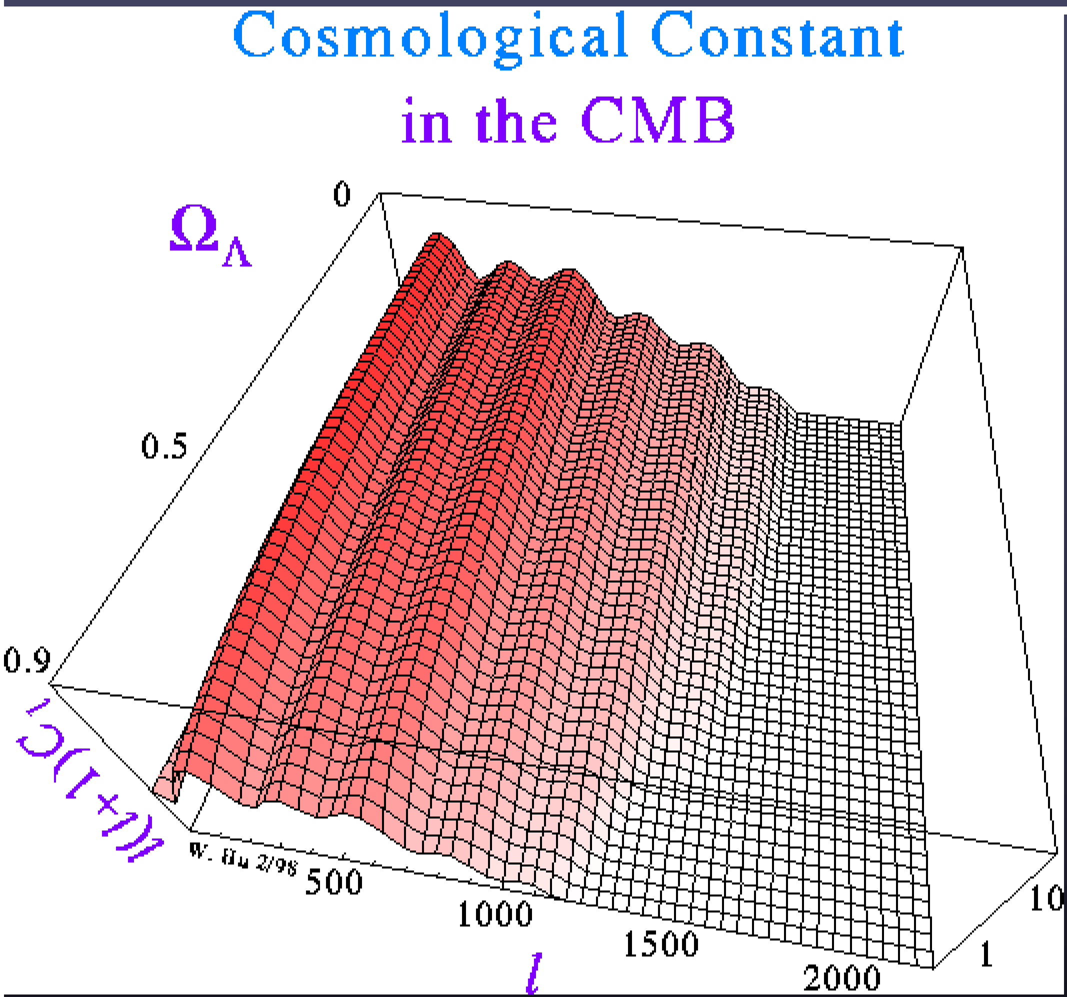
# Peaks and Lambda




Changing dark energy (at fixed curvature) only slight change.

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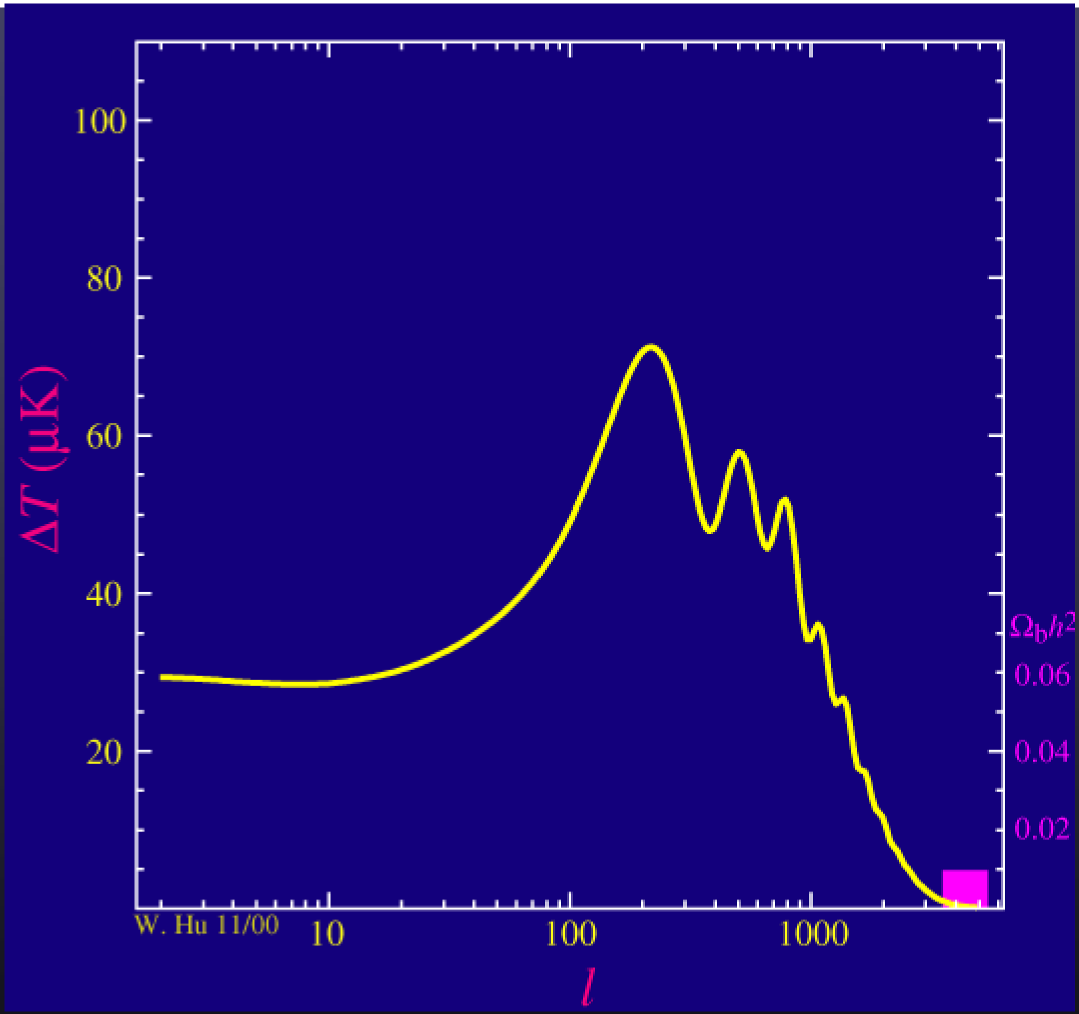
# Peaks and Baryons




Changing baryon loading changes odd/even peaks

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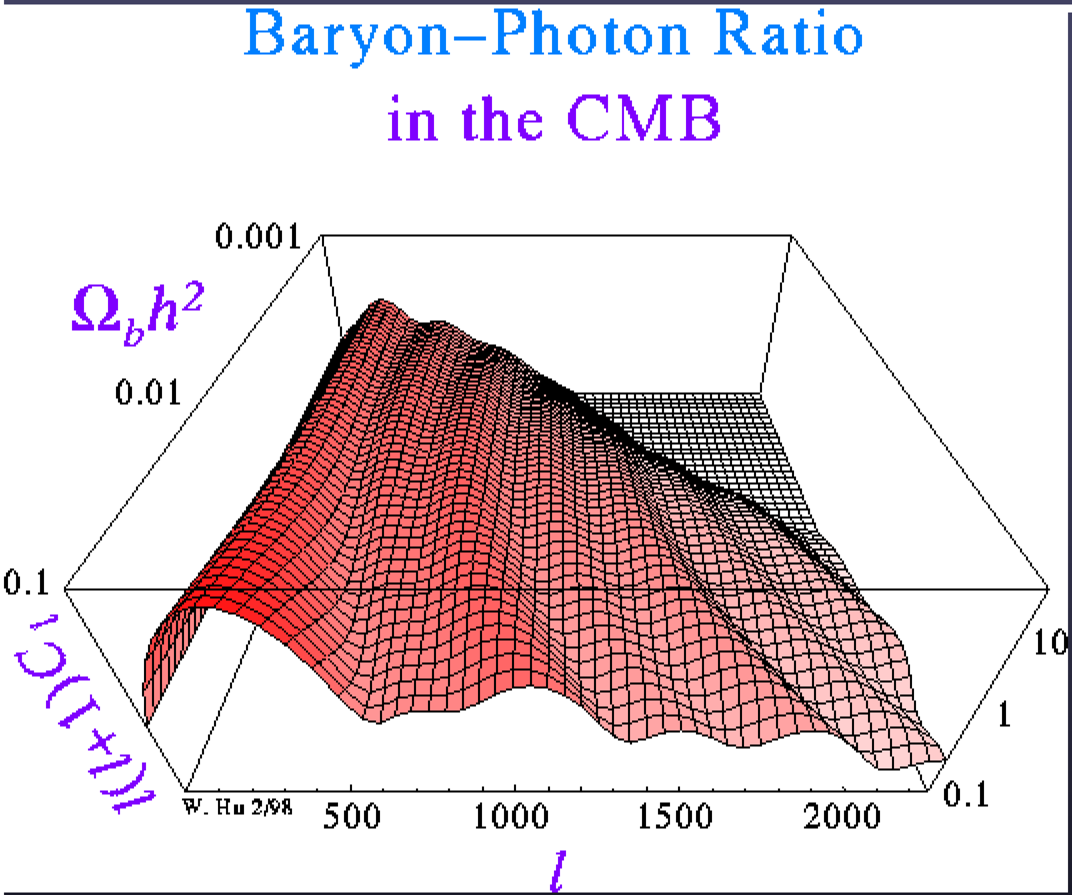


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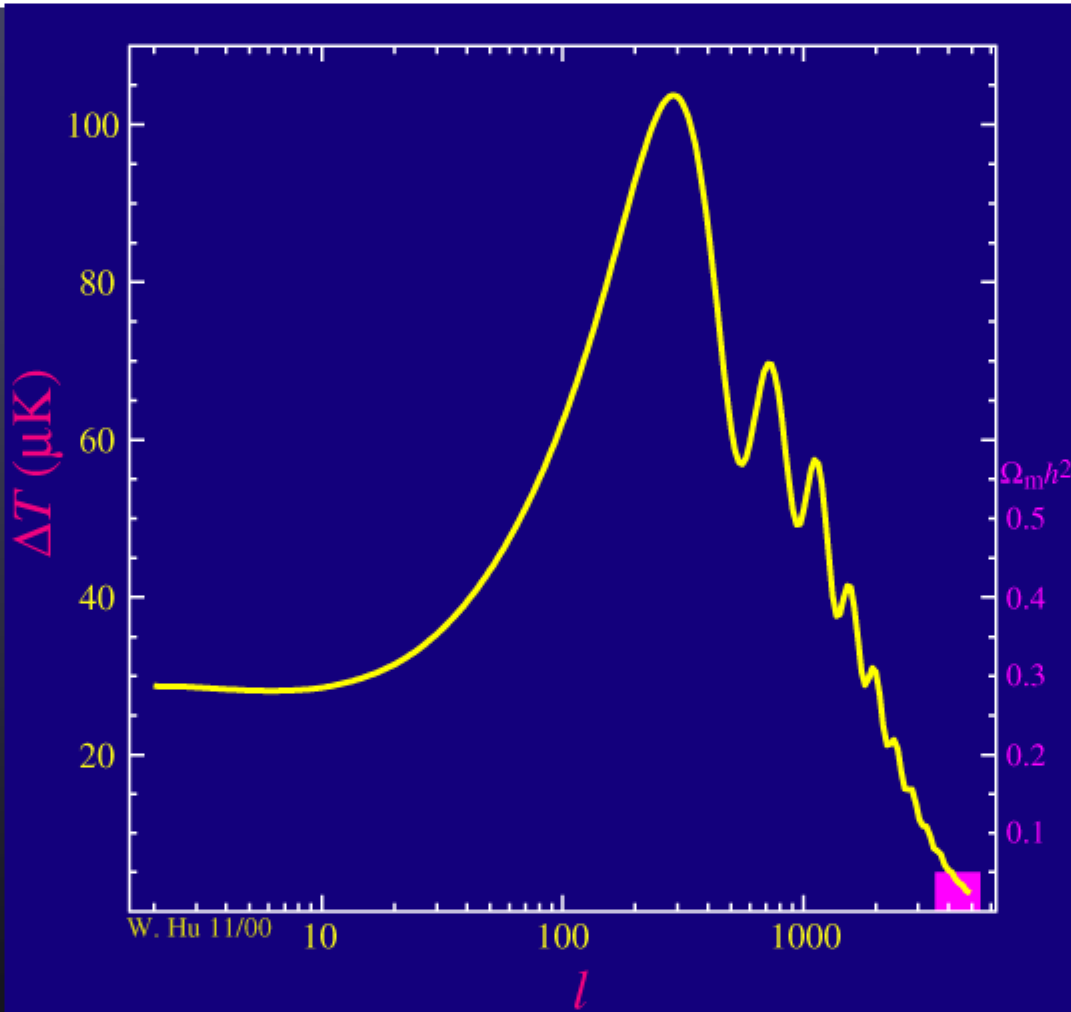
# Peaks and Matter




Changing dark matter density also changes peaks…

- Location and height of acoustic peaks
  - determine values of cosmological parameters
- Relevant parameters
  - curvature of Universe (e.g. open, flat, closed)
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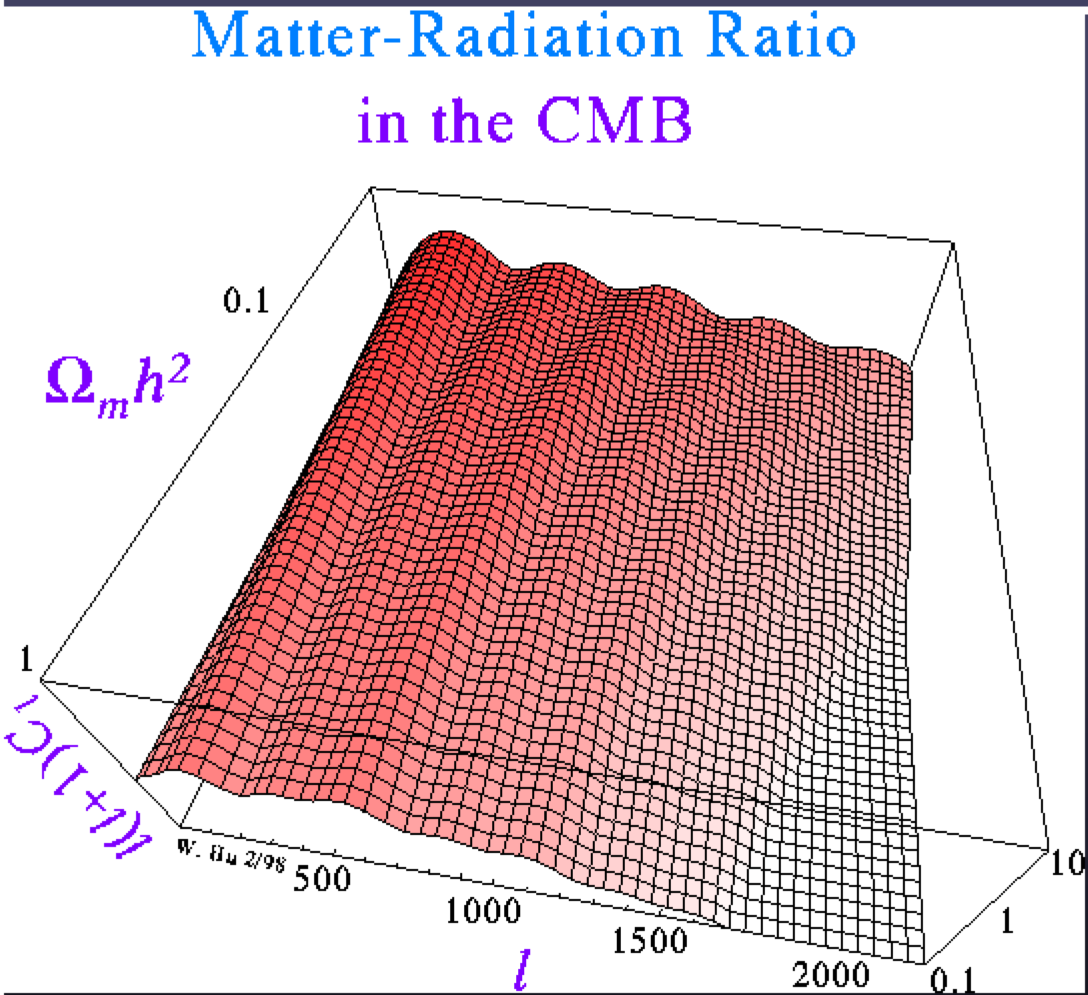


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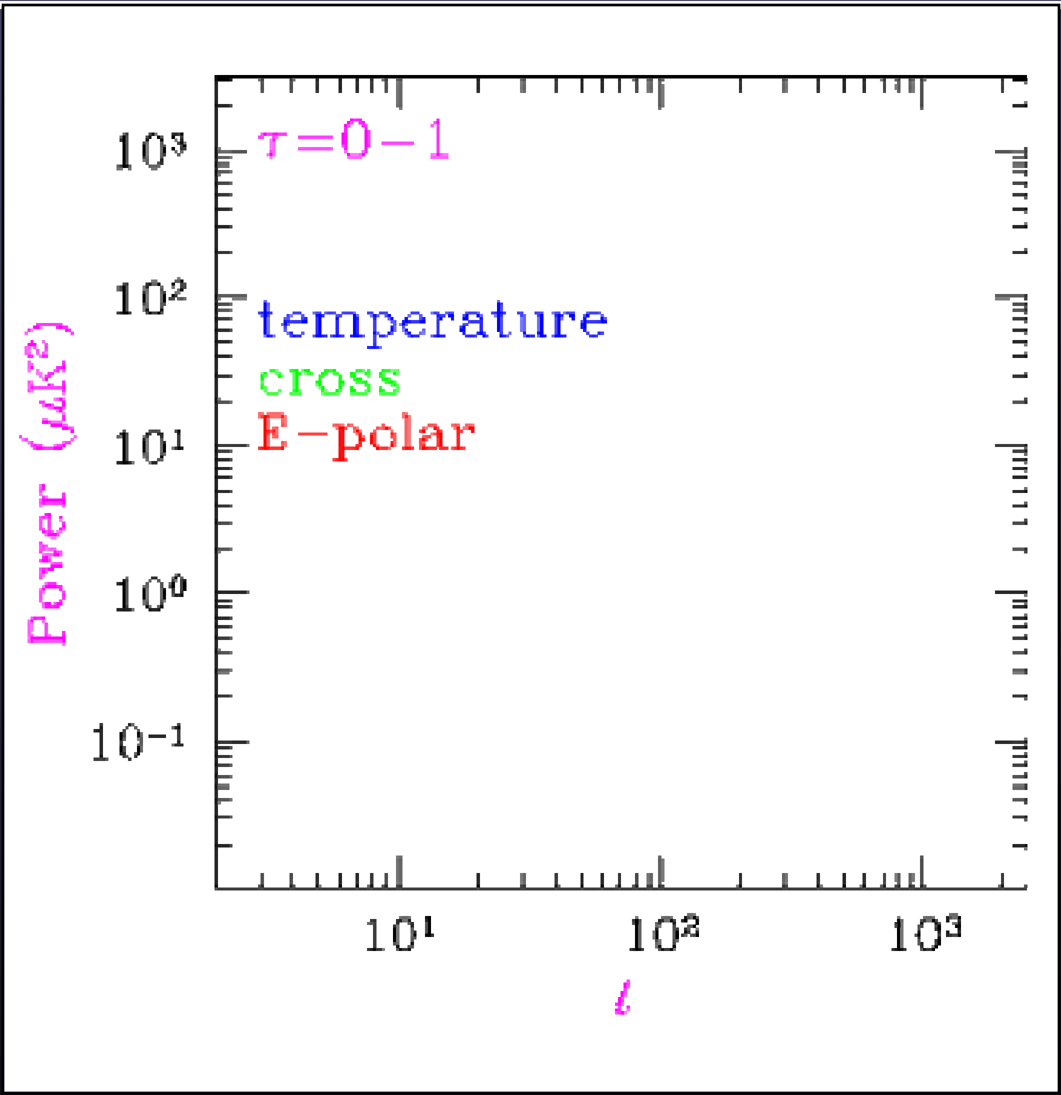
# Reionization




Late reionization reprocesses CMB photons

- Supression of primary temperature anisotropies
  - as exp(-τ)
  - degenerate with amplitude and tilt of spectrum
- Enhancement of polarization
  - low ℓ modes E & B increased
- Second-order conversion of T into secondary anisotropy
  - not shown here
  - velocity modulated effects
  - high ℓ modes

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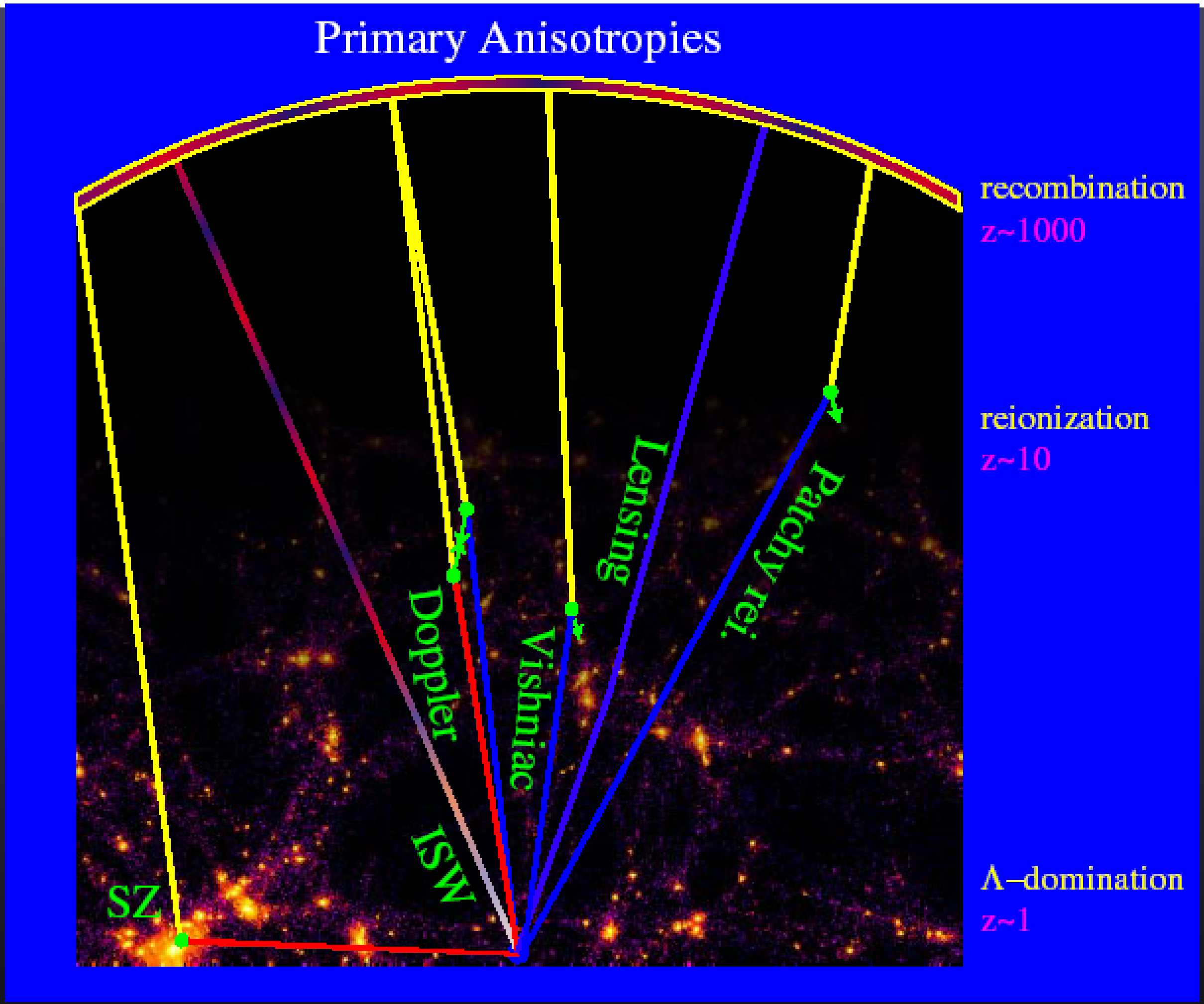
# CMB Checklist

Primary predictions from inflation-inspired models:

- acoustic oscillations below horizon scale
  - nearly harmonic series in sound horizon scale
  - signature of super-horizon fluctuations (horizon crossing starts clock)
  - even-odd peak heights baryon density controlled
  - a high third peak signature of dark matter at recombination
- nearly flat geometry
  - peak scales given by comoving distance to last scattering
- primordial plateau above horizon scale
  - signature of super-horizon potential fluctuations (Sachs-Wolfe)
  - nearly scale invariant with slight red tilt ($n \approx 0.96$) and small running
- damping of small-scale fluctuations
  - baryon-photon coupling plus delayed recombination (& reionization)

# Secondary Anisotropies

# The CMB After Last Scattering…




Secondary Anisotropies from propagation and late-time effects

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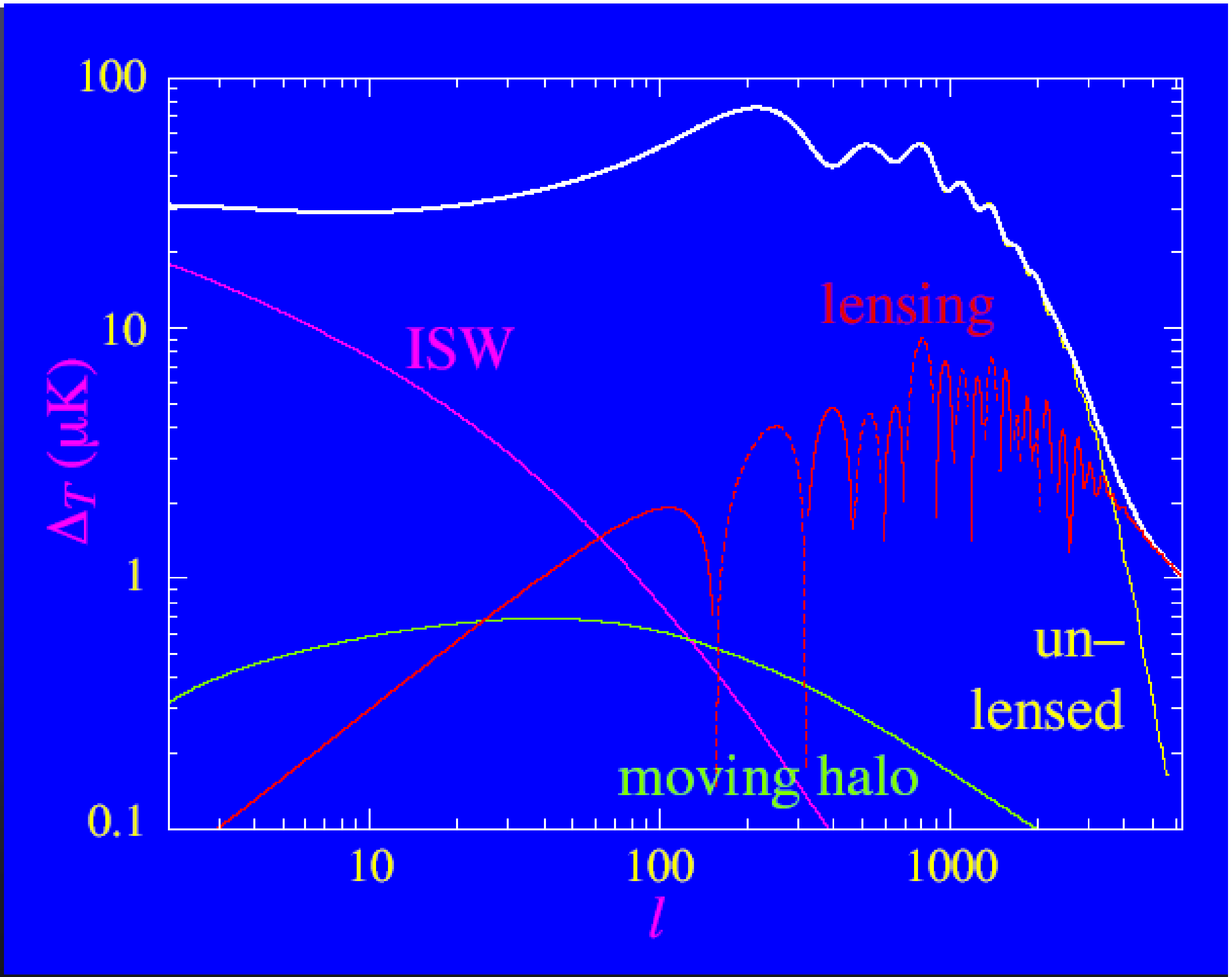
# Gravitational Secondaries

- Due to CMB photons passing through potential fluctuations (spatial and temporal)
- Includes:
  - Early ISW (decay, matter-radiation transition at last scattering)
  - Late ISW (decay, in open or lambda model)
  - Rees-Sciama (growth, non-linear structures)
  - Tensors (gravity waves, 'nuff said)
  - Lensing (spatial distortions)

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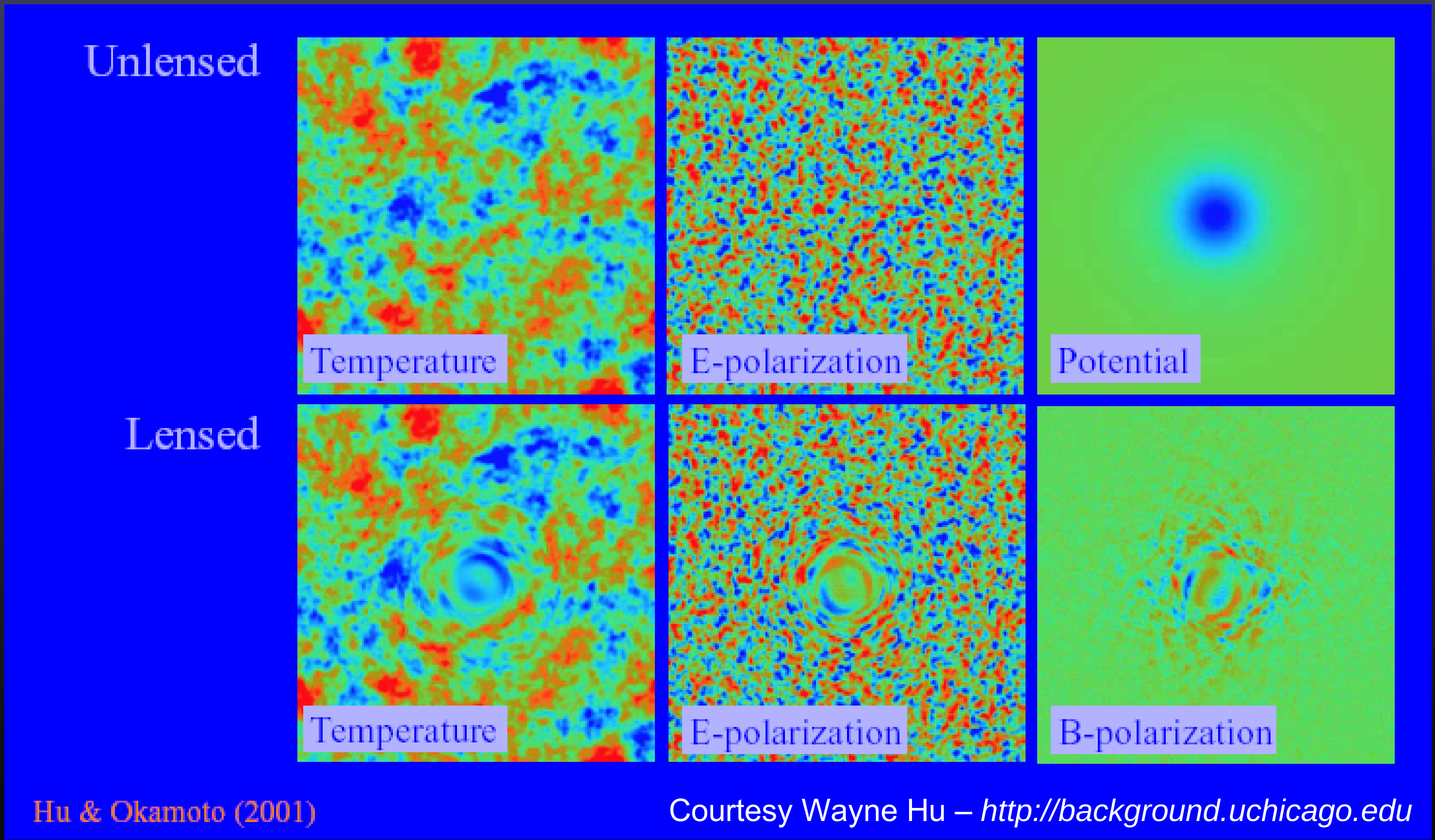
# CMB Lensing

- Distorts the background temperature and polarization
- Converts E to B polarization
- Can reconstruct from T,E,B on arcminute scales
- Can probe clusters

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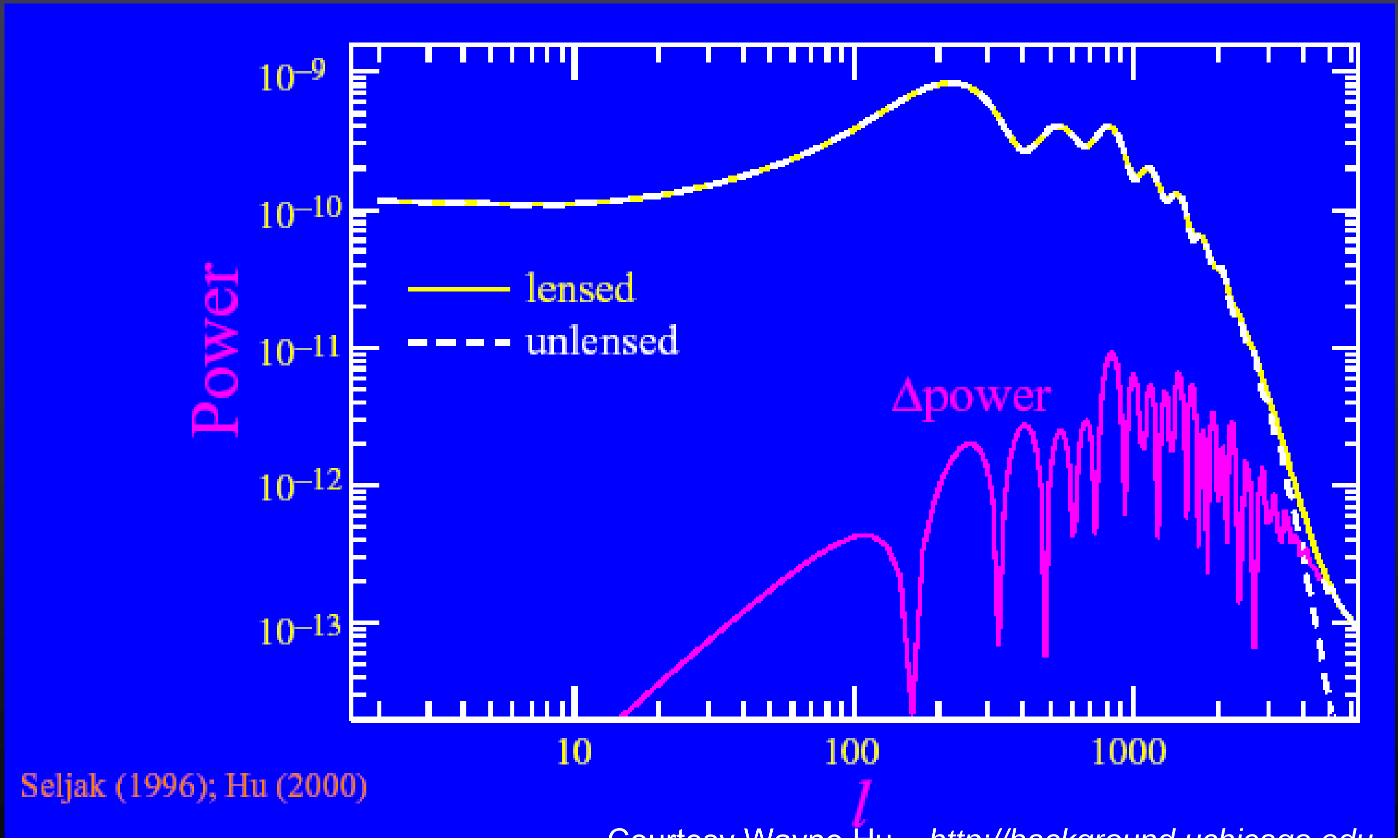


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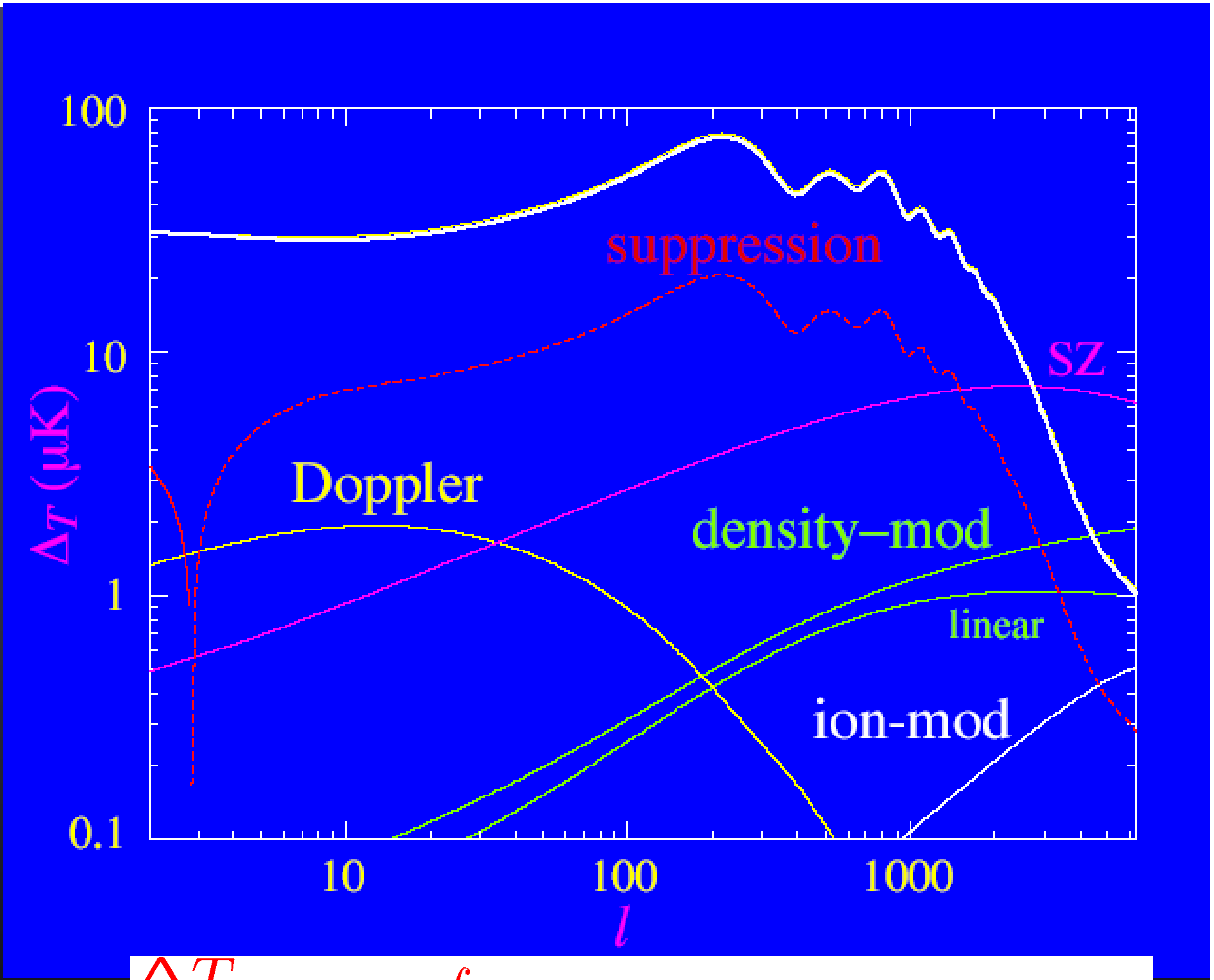
# Scattering Secondaries

- Due to variations in:
  - Density
    - Linear = Vishniac effect
    - Clusters = thermal Sunyaev-Zeldovich effect
  - Velocity (Doppler)
    - Clusters = kinetic SZE
  - Ionization fraction
    - Coherent reionization suppression
    - “Patchy” reionization




$$\frac{\Delta T}{T}(\hat{n}) = \int dx\,(n_e\,\sigma_T\,e^{-\tau})\,\hat{n}\cdot\mathbf{v}(\mathbf{x},z)$$

$$n_e = X_e\,n_p = \bar{X}_e\,\bar{n}_p(1+\delta_x+\delta_b)$$

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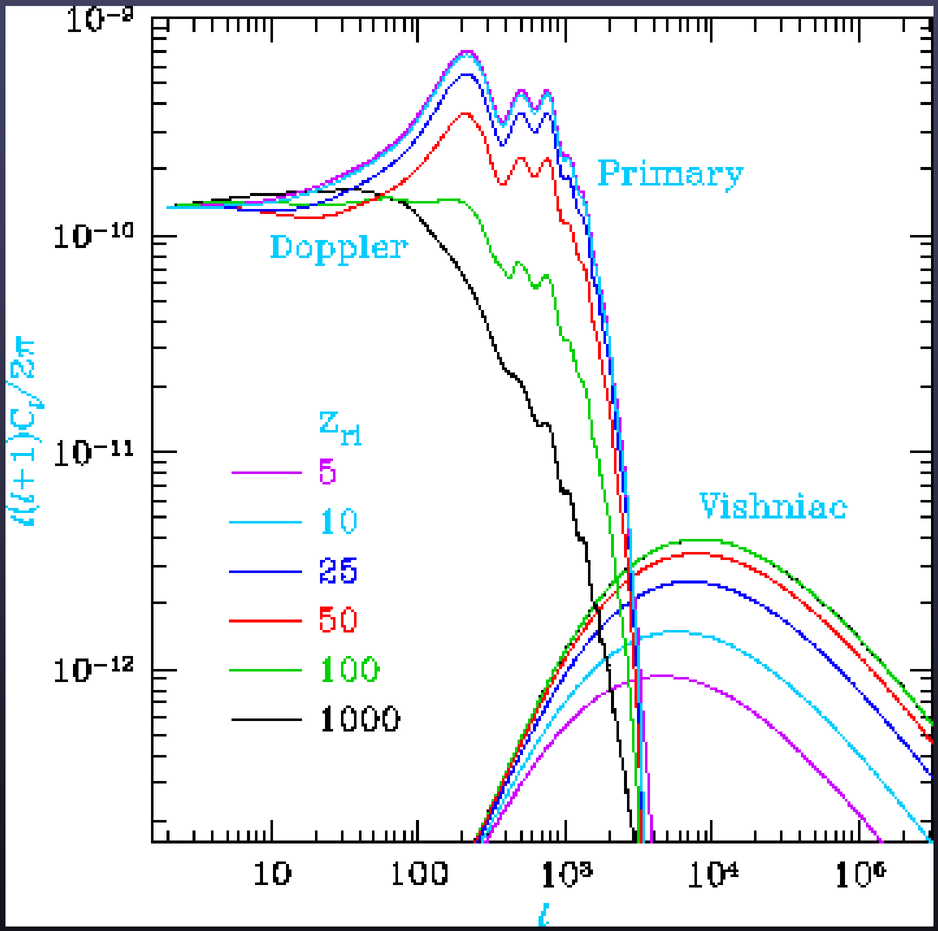
# Ostriker-Vishniac Effect

- Reionization + Structure
  - Linear regime
  - Second order (not cancelled)
  - Reionization supresses large angle fluctuations but generates small angle anisotropies

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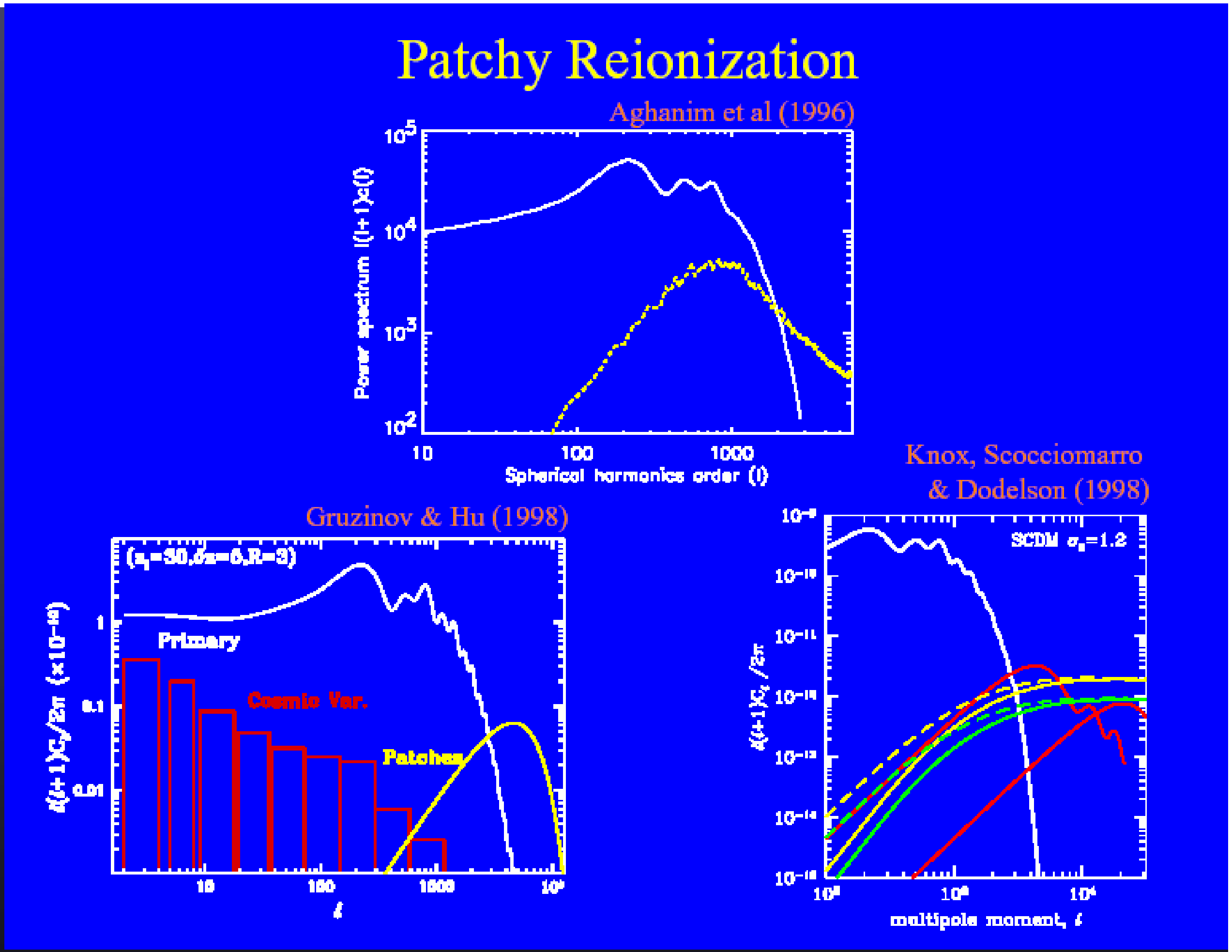
# Patchy Reionization

- Structure in ionization
  - Can distinguish between ionization histories
  - Confusion, e.g. kSZ effect
  - e.g. Santos et al. (0305471)
- Effects similar
  - kSZ, OV, PReI
  - Different z's, use lensing?



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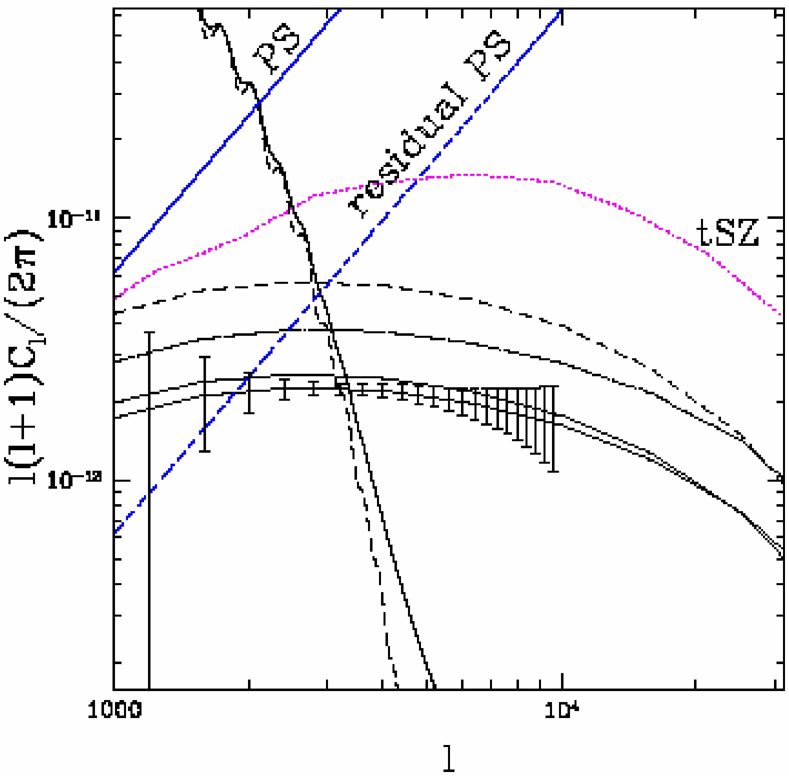
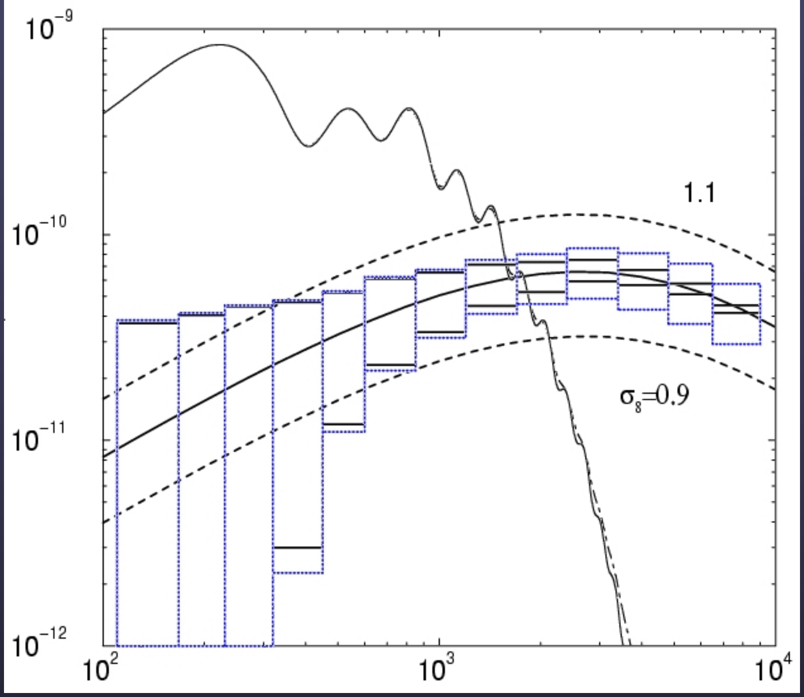


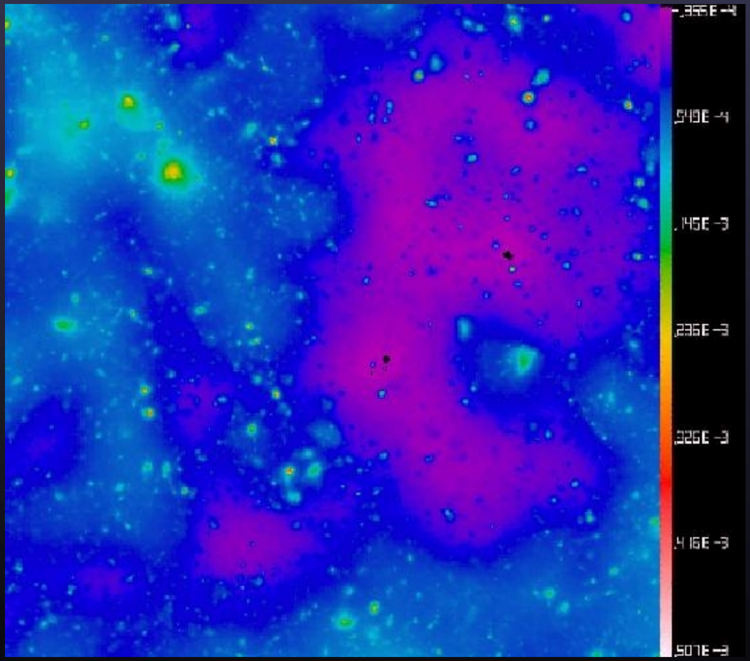

FIG. 5.— Patchy power spectra for the reionization models in Figure 3 (same line styles), together with other astrophysical contributions and expected measurement errors (see text). The solid (dashed) straight line is the the point source contribution at 217 GHz before (after) multi-frequency cleaning. The primary unlensed (dashed) and lensed (solid) CMB power spectra are also shown as is the thermal SZ power spectrum from White et al. (2002) (dotted) with its expected amplitude at lower frequencies. The thin line close to the solid one shows the patchy power spectrum for a model with $\tau = 0.11$ but large bias.

# Sunyaev-Zeldovich Effect (SZE)

- Spectral distortion of CMB
- Dominated by massive halos (galaxy clusters)
- Low-z clusters: ~ 20'-30'
- z=1: ~1' → expected dominant signal in CMB on small angular scales
- Amplitude highly sensitive to $\sigma_8$




A. Cooray (astro-ph/0203048)



P. Zhang, U. Pen, & B. Wang (astro-ph/0201375)

# CMB Checklist (continued)

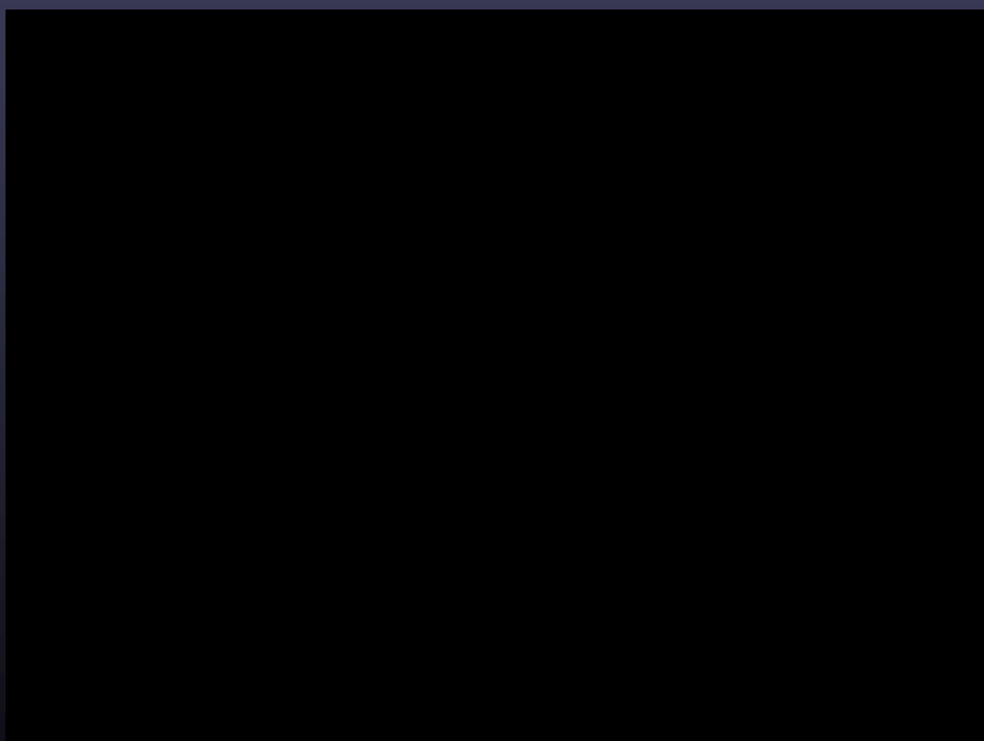
Secondary predictions from inflation-inspired models:

- late-time dark energy domination
  - low $\ell$ ISW bump correlated with large scale structure (potentials)
- late-time non-linear structure formation
  - gravitational lensing of CMB
  - Sunyaev-Zeldovich effect from deep potential wells (clusters)
- late-time reionization
  - overall supression and tilt of primary CMB spectrum
  - doppler and ionization modulation produces small-scale anisotropies

# Matter Spectrum and Large Scale Structure

# After recombination …

- Potential fluctuations grow to form Large Scale Structure
  - overdensities collapse to form galaxies and galaxy clusters
  - underdensities expand into voids, with cosmic web between
  - acoustic peaks appear as Baryon Oscillations in matter spectrum



Simulation courtesy A. Kravtsov – *http://cosmicweb.uchicago.edu*

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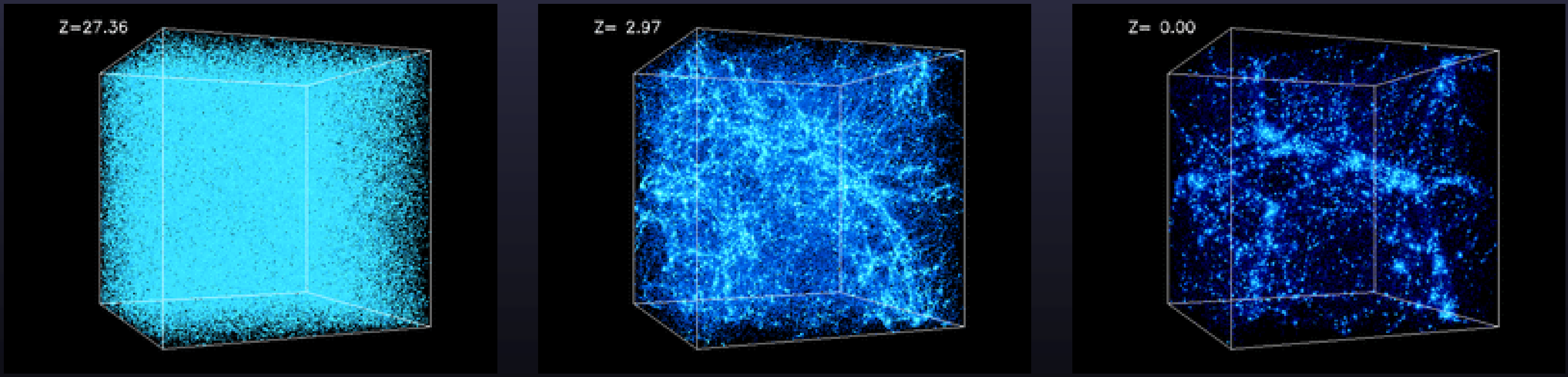
- Potential fluctuations grow to form Large Scale Structure
  - overdensities collapse to form galaxies and galaxy clusters
  - underdensities expand into voids, with cosmic web between
  - acoustic peaks appear as Baryon Oscillations in matter spectrum
- Current overdensities in non-linear regime
  - $\delta\rho/\rho \sim 1$ on 8 $h^{-1}$ Mpc scales ($\sigma_8$ parameter)
  - linear potential growth: $\delta\rho/\rho \sim$ 10-3 at recombination ($z \approx 1500$)

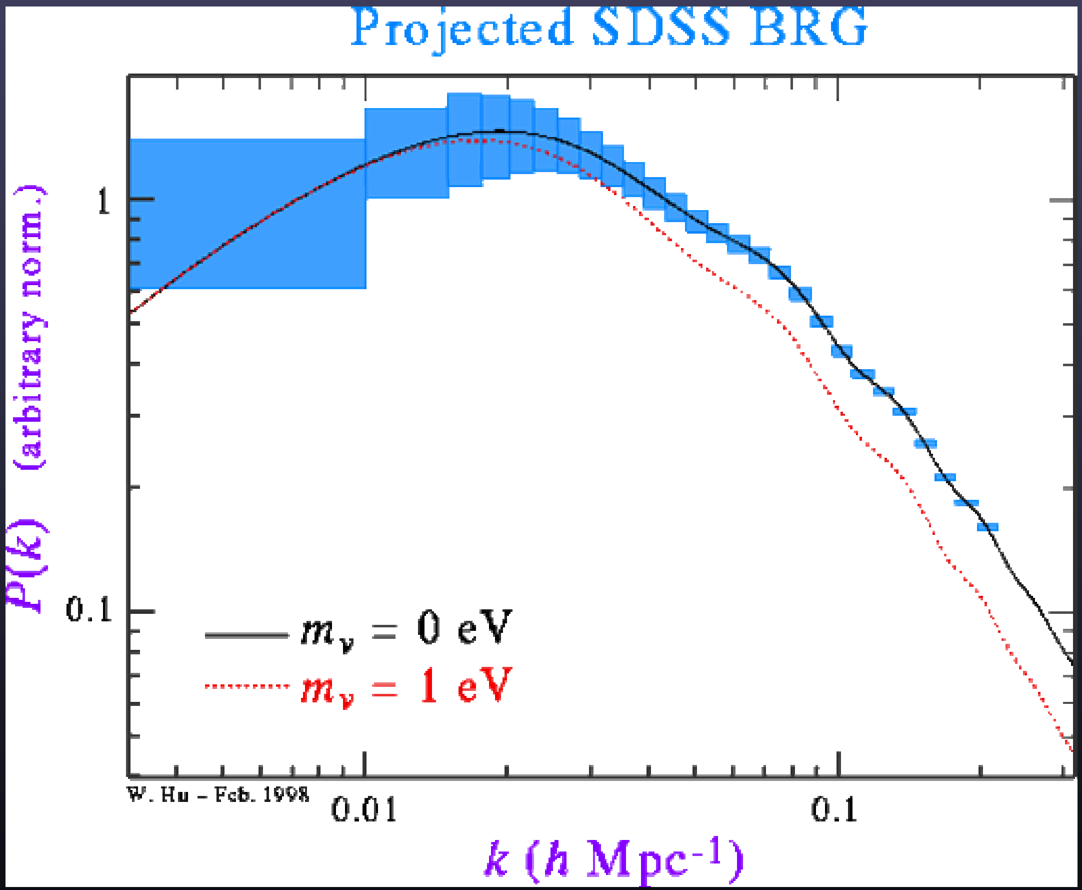



Simulation courtesy A. Kravtsov – *http://cosmicweb.uchicago.edu*

# Late Times: Matter Power Spectrum

- matter power spectrum P(k)
  - related to angular power spectrum (via transfer function)

- <u>large scale structure</u>
  - non-linear on small scales (<10 Mpc = 0.1)
  - imprint of CMB acoustic peaks retained on large scales
  - “baryon oscillations” measured by SDSS

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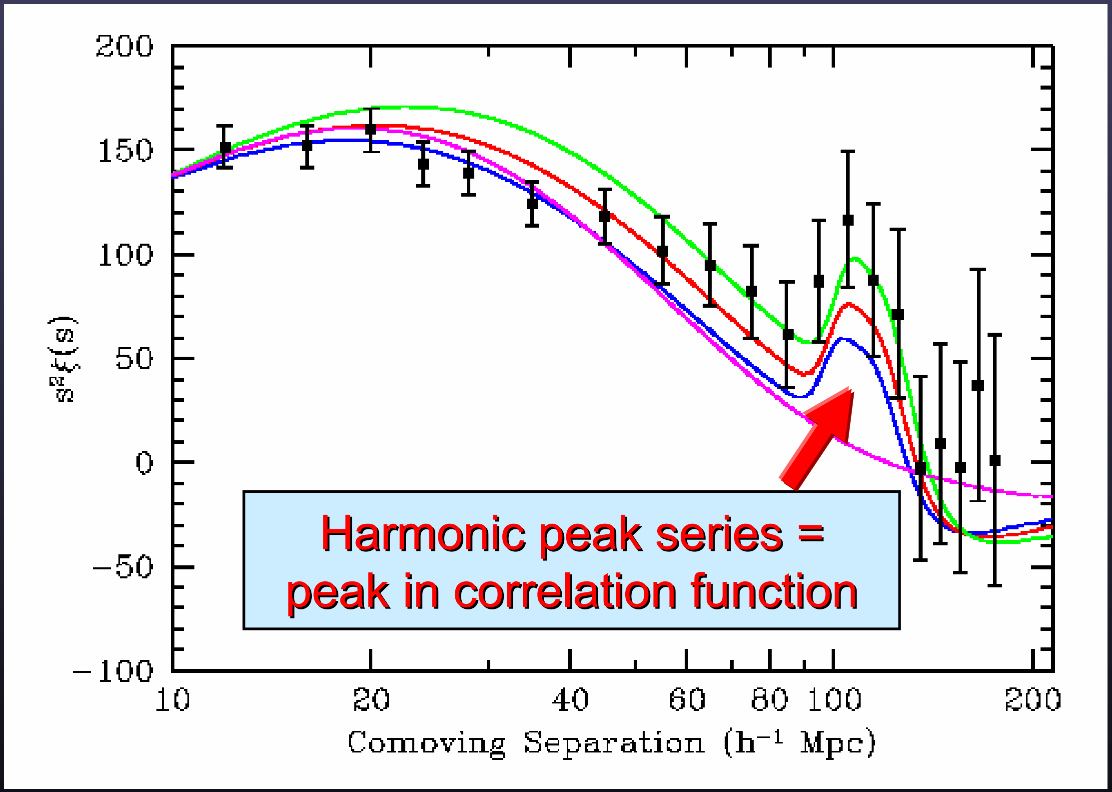


Eisenstein et al. 2005, astro-ph/0501171

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- late-time reionization
  - overall supression and tilt of primary CMB spectrum
  - doppler and ionization modulation produces small-scale anisotropies
- growth of matter power spectrum
  - primordial power-law above current sound horizon
  - CMB acoustic peaks as baryon oscillations