Sterrewacht Leiden

Origins & Evolution of the Universe

an introduction to cosmology – Fall 2014

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http://www.strw.leidenuniv.nl/~hoekstra/TEACHING/OEU/OEU.html

Statistics of matter fluctuation

The initial density fluctuations grow at different rates depending on scale of the fluctuation and we end up with a field of density fluctuations:

$$\delta(x) = \frac{\delta\rho(x)}{\bar{\rho}}$$

which is a superposition of all these fluctuations. It is interesting to consider the statistics of this field using its Fourier transform

$$\delta(k) = \int d^3x \cdot e^{-ik\cdot x}\delta(x)$$

Because each mode δ(k) obeys the growth equation as long as the proper wavelength 2πa(t)/k is large compared to the Jeans length and small compared to the Hubble distance.

Statistics of matter fluctuation

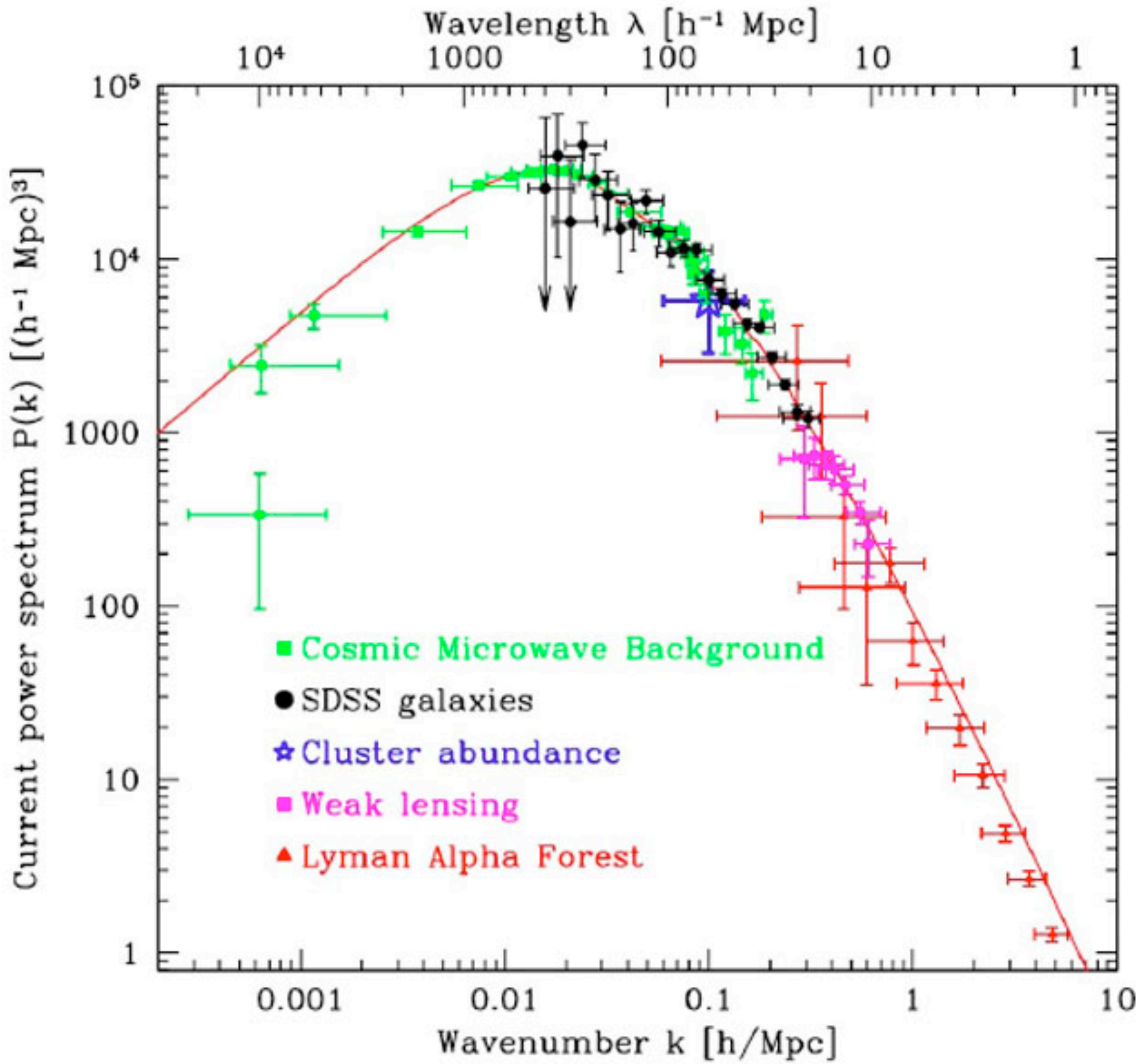
The mean square amplitude of the Fourier components defines the power spectrum of the fluctuations:

$$\left\langle \delta(k)\delta^*(k') \right\rangle = (2\pi)^3 \delta_D(k-k')P(k)$$

The power spectrum is therefore the Fourier transform of the two-point correlation function

$$\xi(r) = \left\langle \delta(x_1)\delta(x_2) \right\rangle = \int \frac{d^3k}{(2\pi)^3} e^{ik\cdot x} P(k)$$

Statistics of matter fluctuation



From Tegmark (2004)

Initial power spectrum

Inflation makes a prediction about the initial power spectrum: $P(k)=Ak^n$, where $n \approx 1$.

The observed power spectrum is clearly different from this simple function: it has been modified by horizon crossings and scale-dependent growth.

The relation between the primordial and current power spectrum is given by the **transfer function** *T(k)*:

$$P(k) = Ak^n T^2(k)$$

Transfer functions

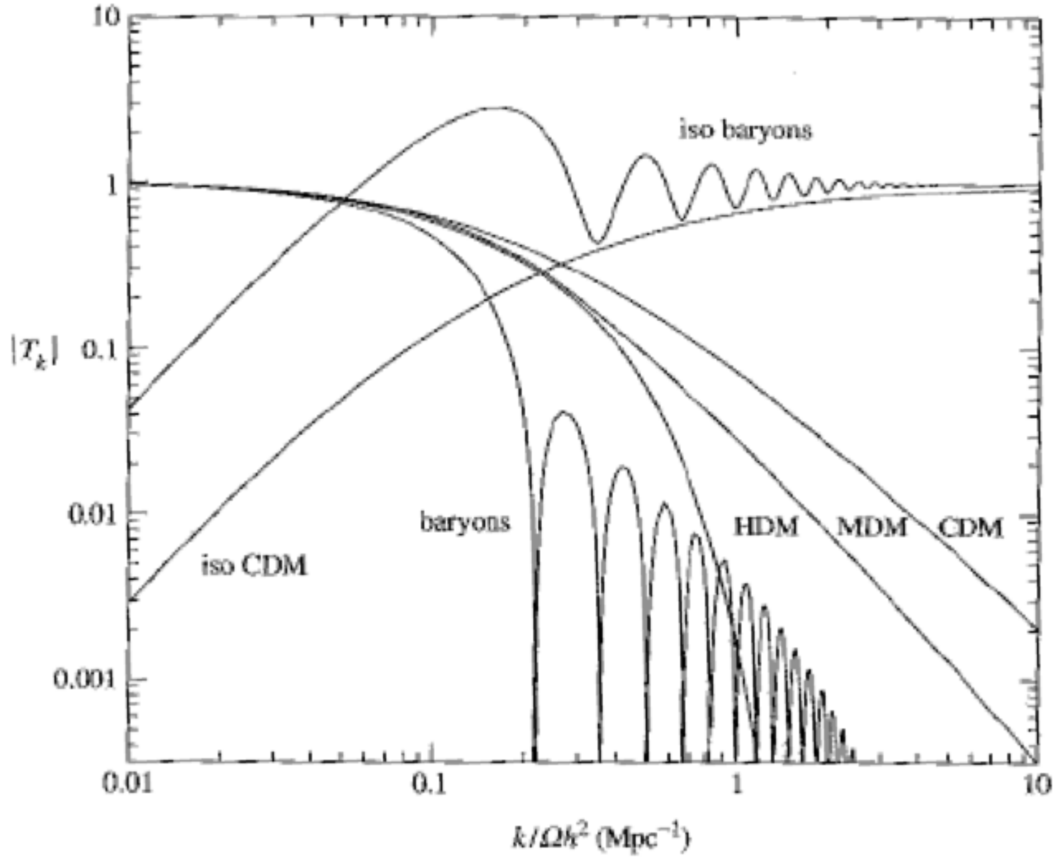


Figure 15.1 Examples of adiabatic transfer functions for baryons, hot dark matter (HDM), cold dark matter (CDM) and mixed dark matter (MDM; also known as CHDM). Isocurvature modes are also shown. Picture courtesy of John Peacock.

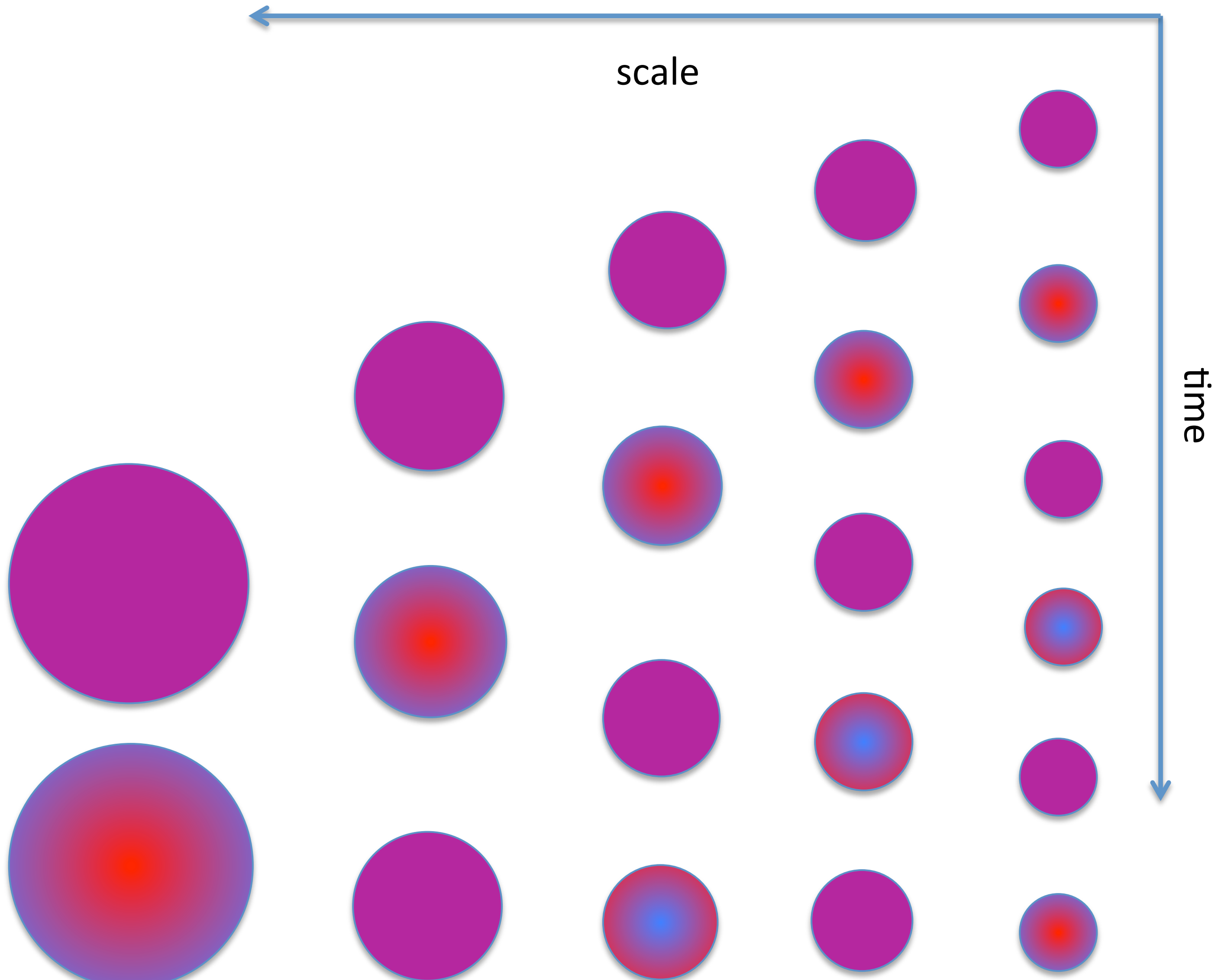
Cosmic Microwave Background

The Cosmic Microwave Background radiation represents a snapshot of the density fluctuations at the time of photon decoupling (time of last scattering).

Some of the oscillating modes will be caught at their maximum, some at their minimum and others in between.

The result is a superposition of these sound waves, which are observed as temperature fluctuations.

Acoustic oscillations



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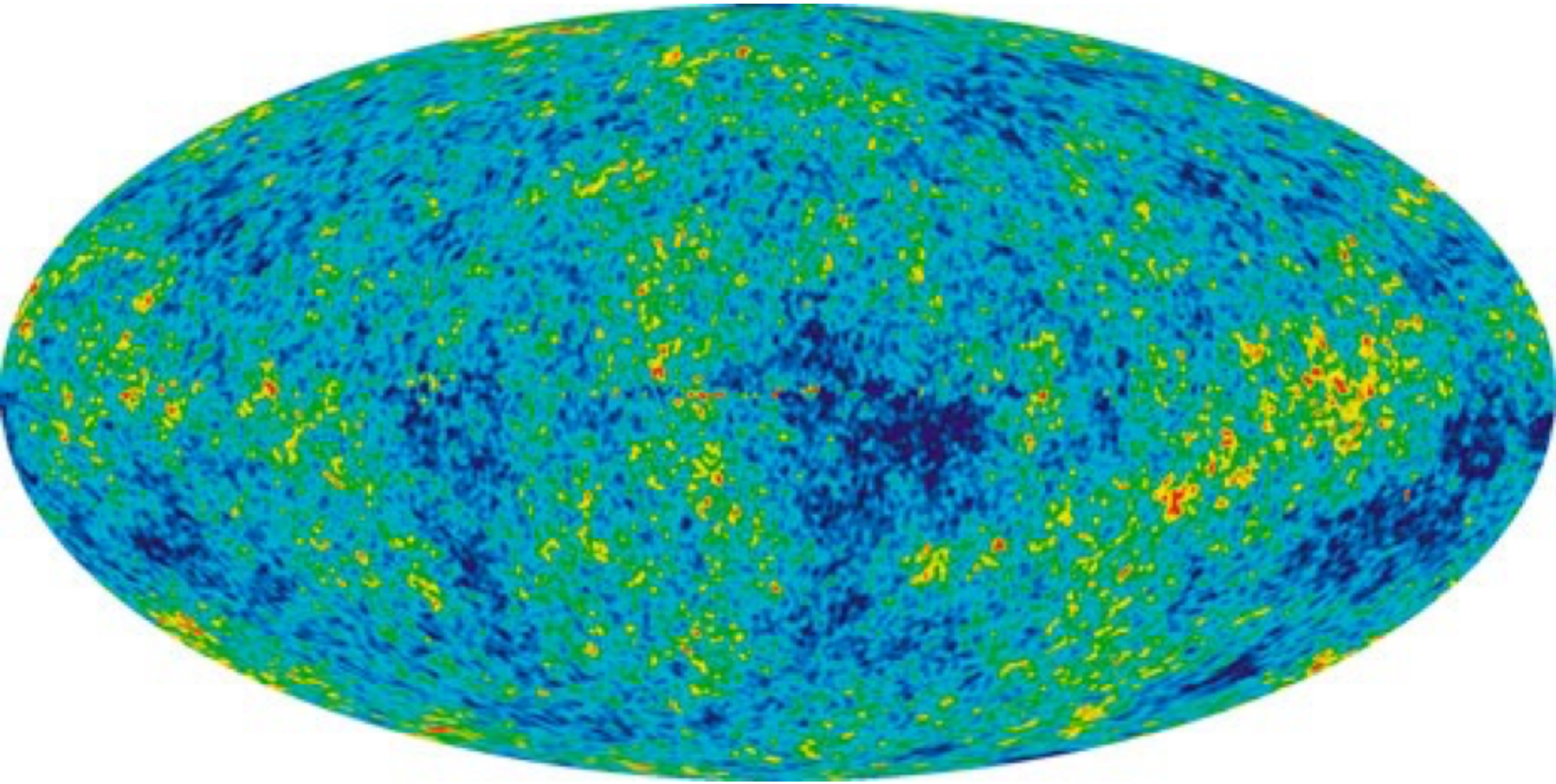
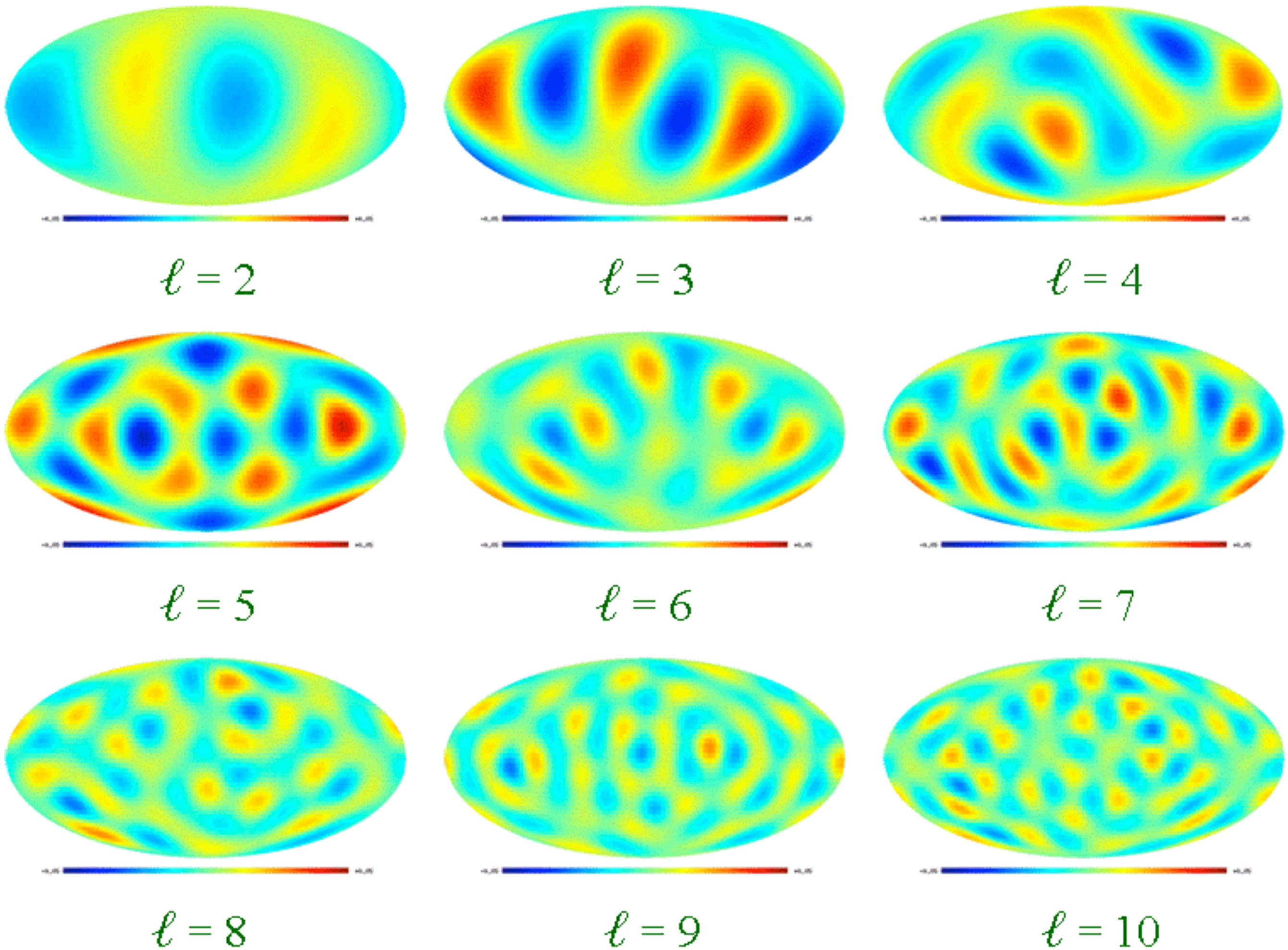
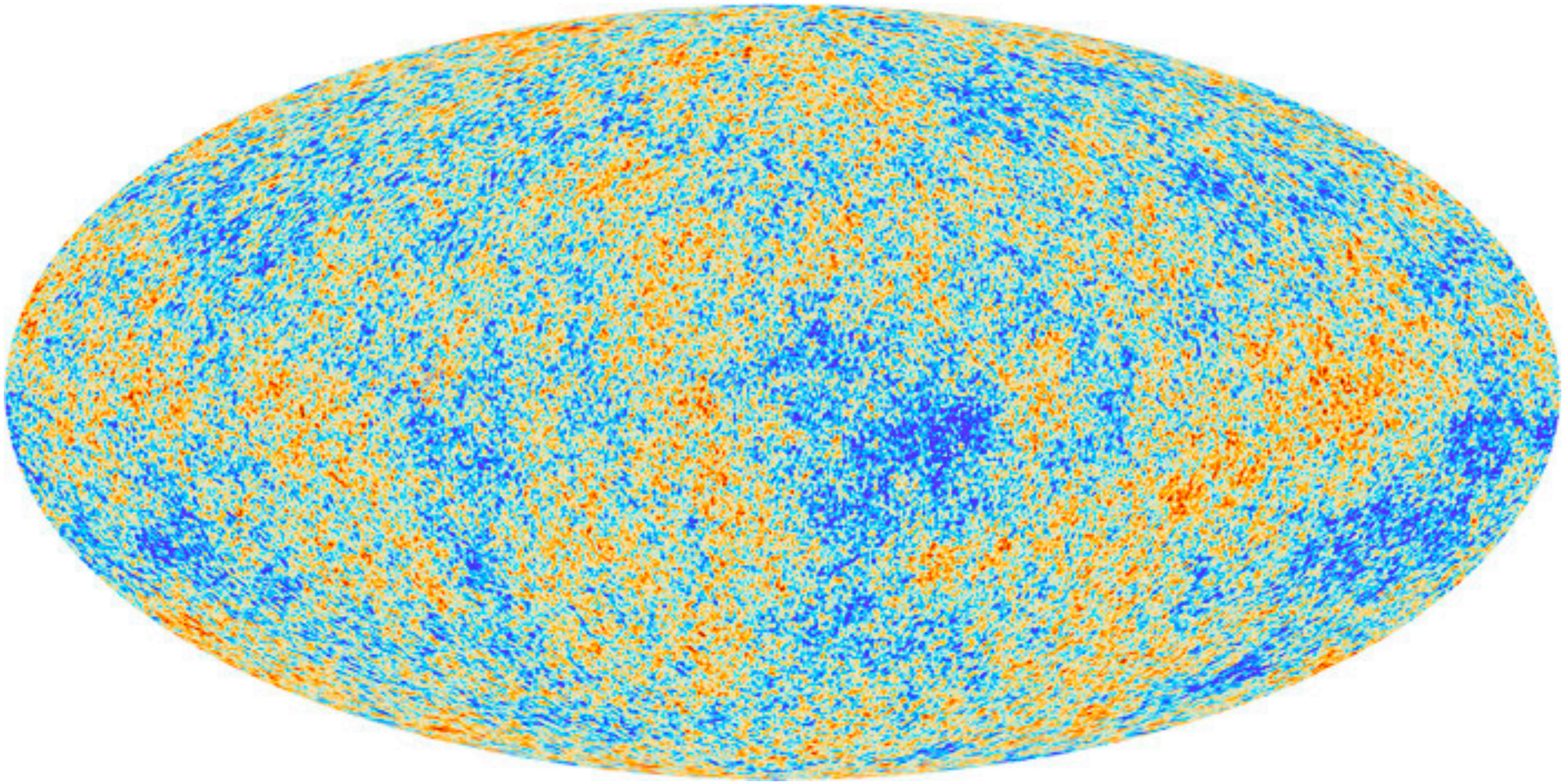
The CMB seen by WMAP



Decomposition of WMAP

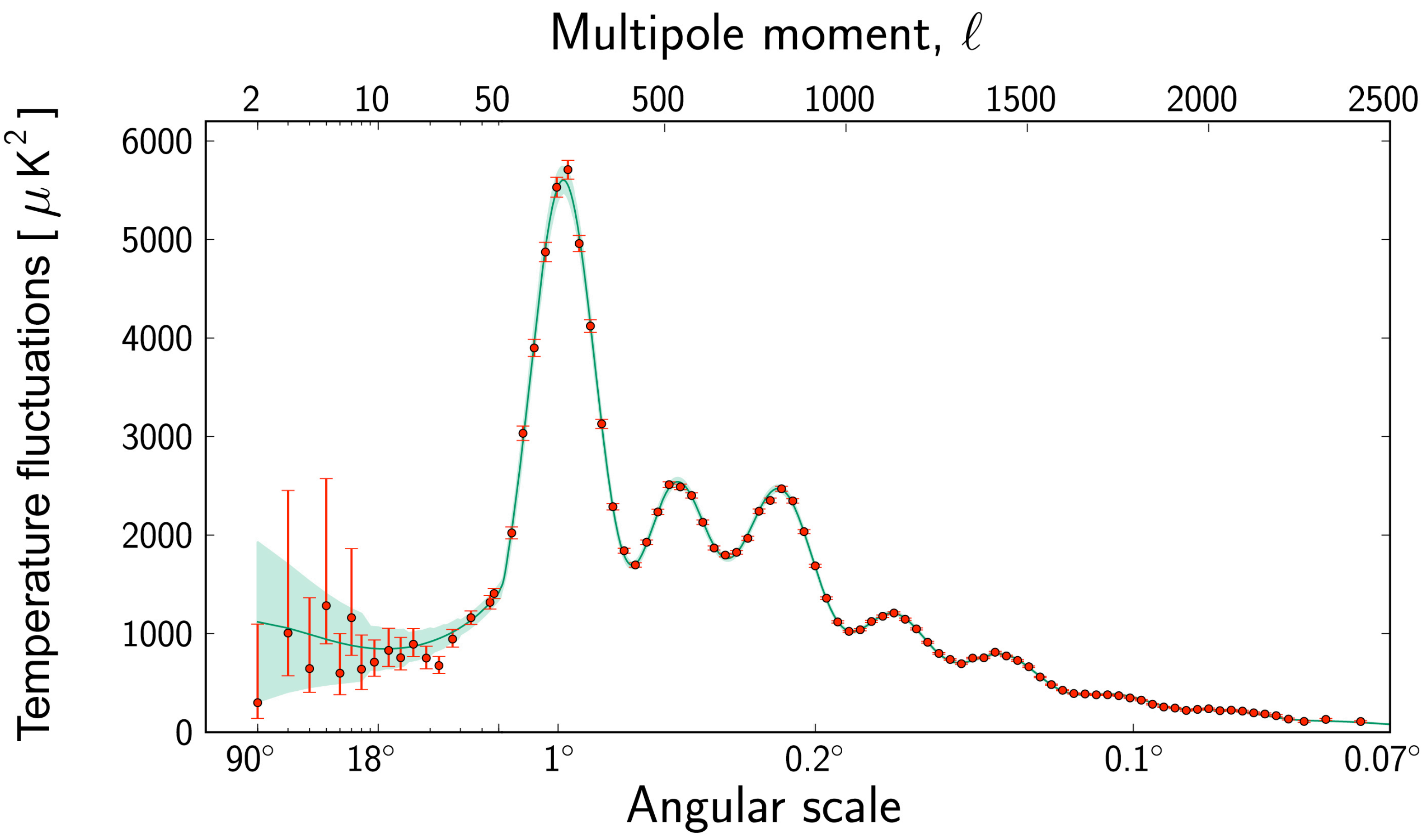


The CMB seen by Planck



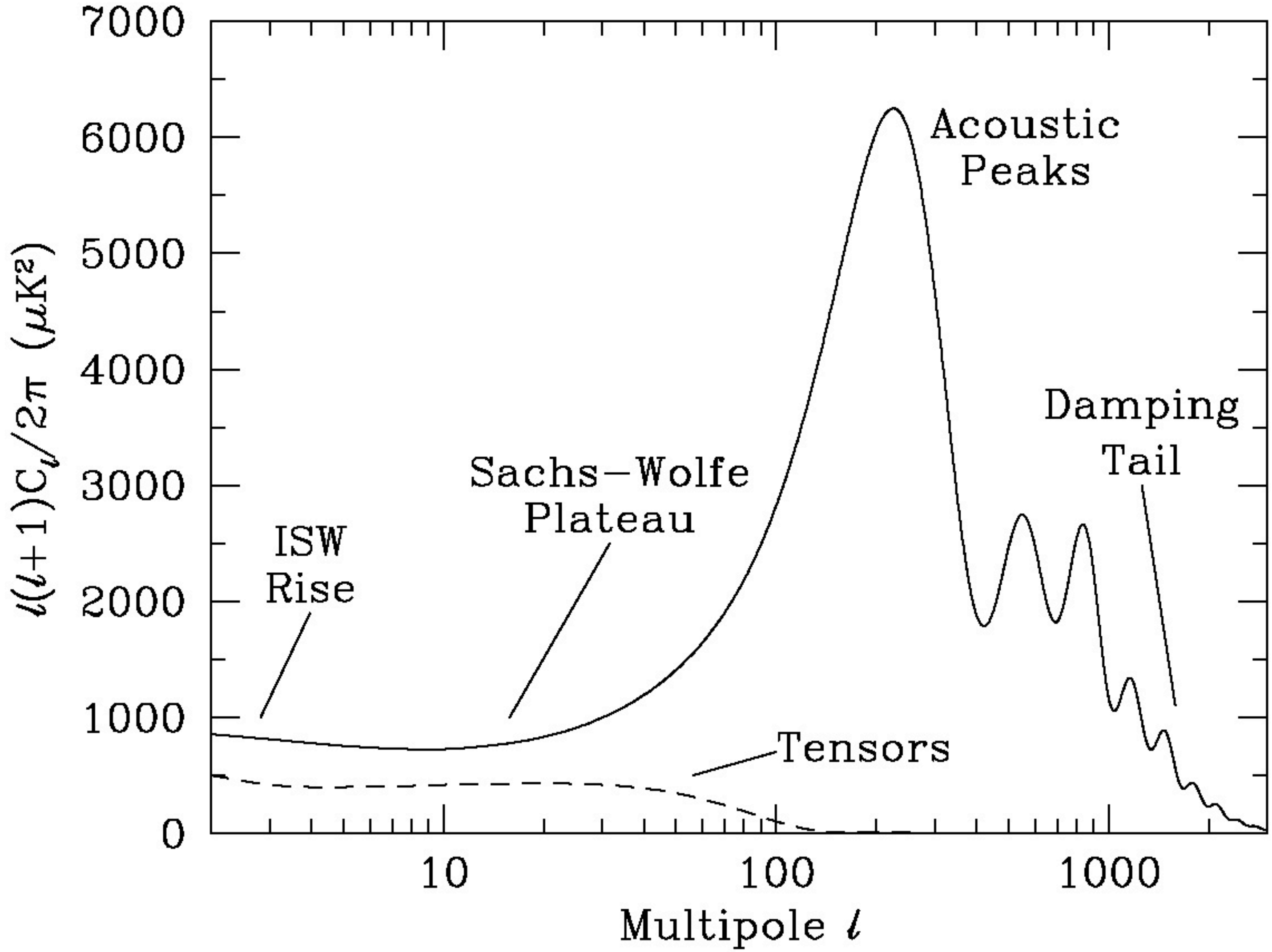
The best possible view of the primary CMB: on large scales we have a limited number of modes and on small scales other effects take over.

Statistics of fluctuation

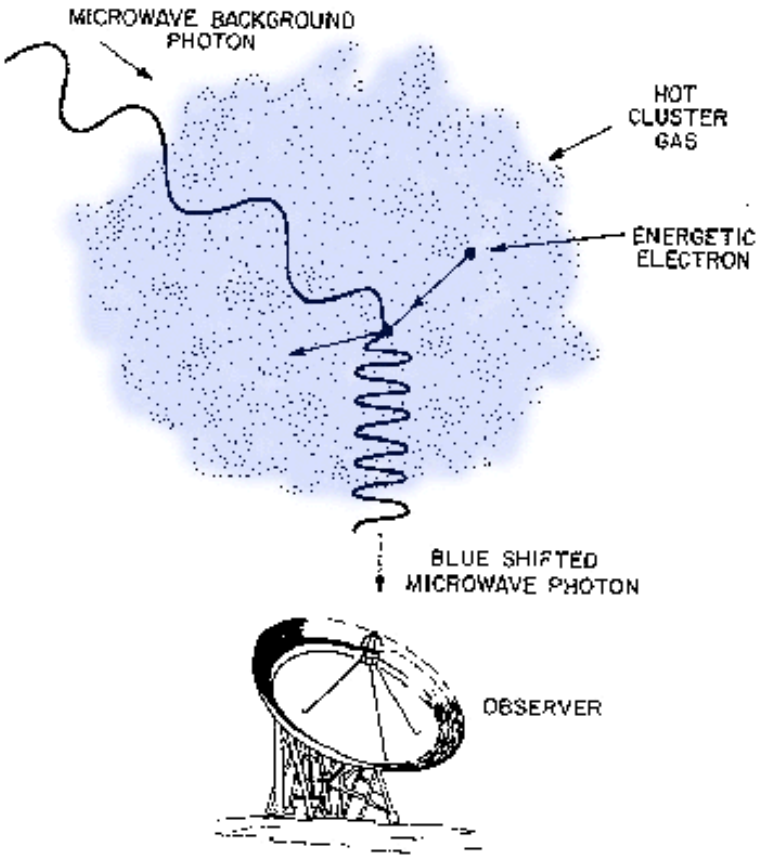


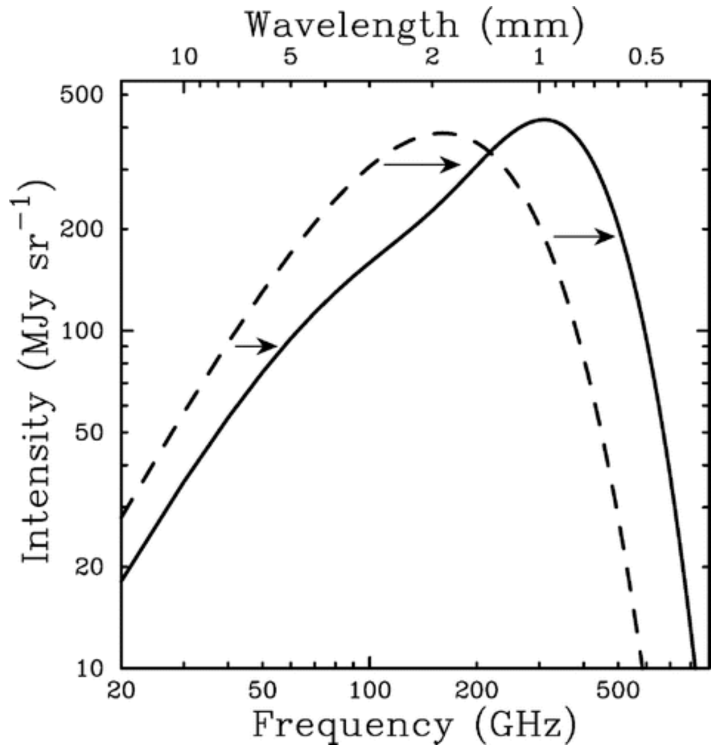
We can indeed predict the power spectrum of fluctuations for a set of initial conditions.

CMB power spectrum



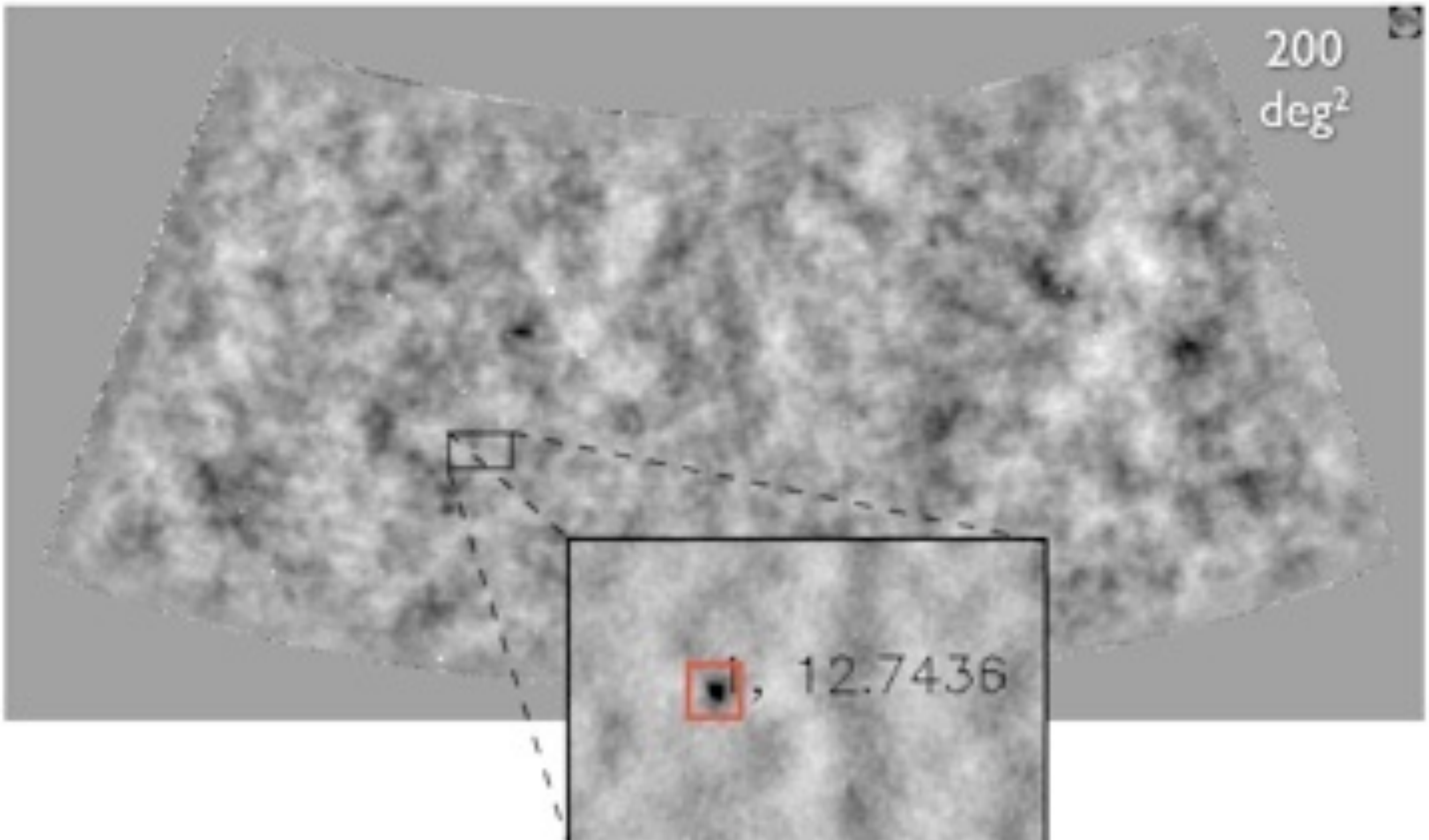
Sunyaev-Zel'dovich Effect





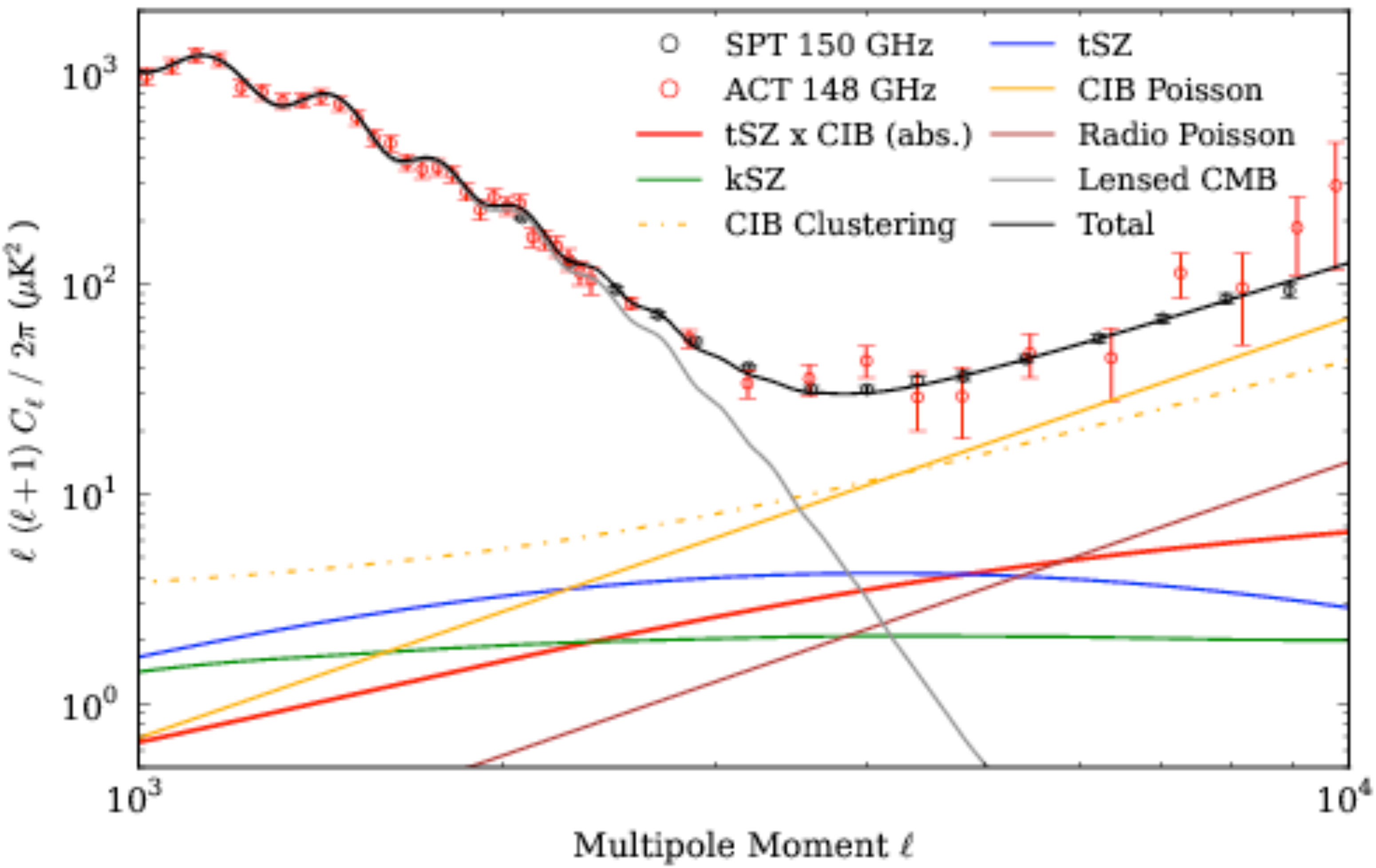
e.g. Carlstrom et al. (2002)

Sunyaev-Zel'dovich Effect



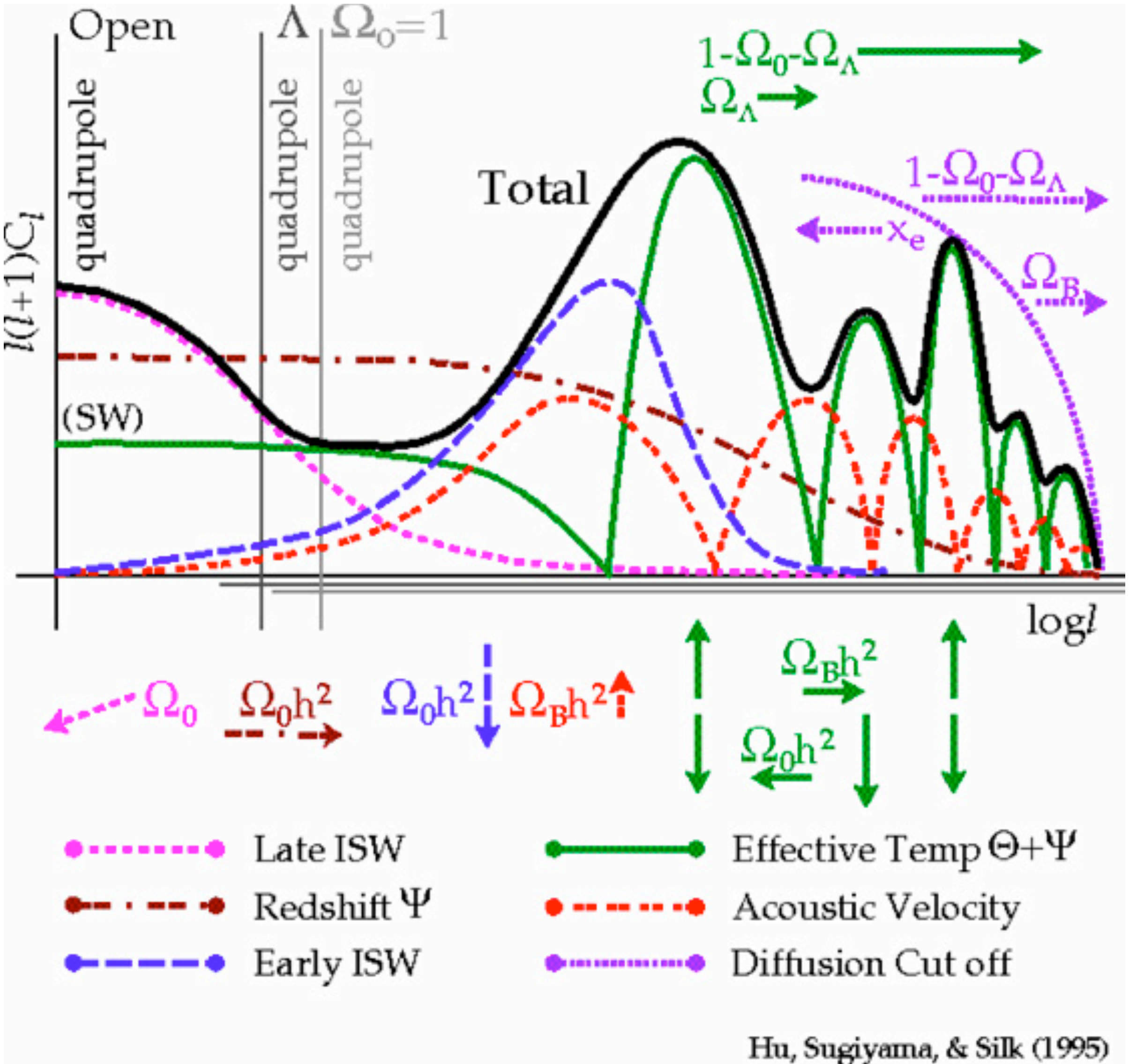
200 square degree SPT map

Many more complications



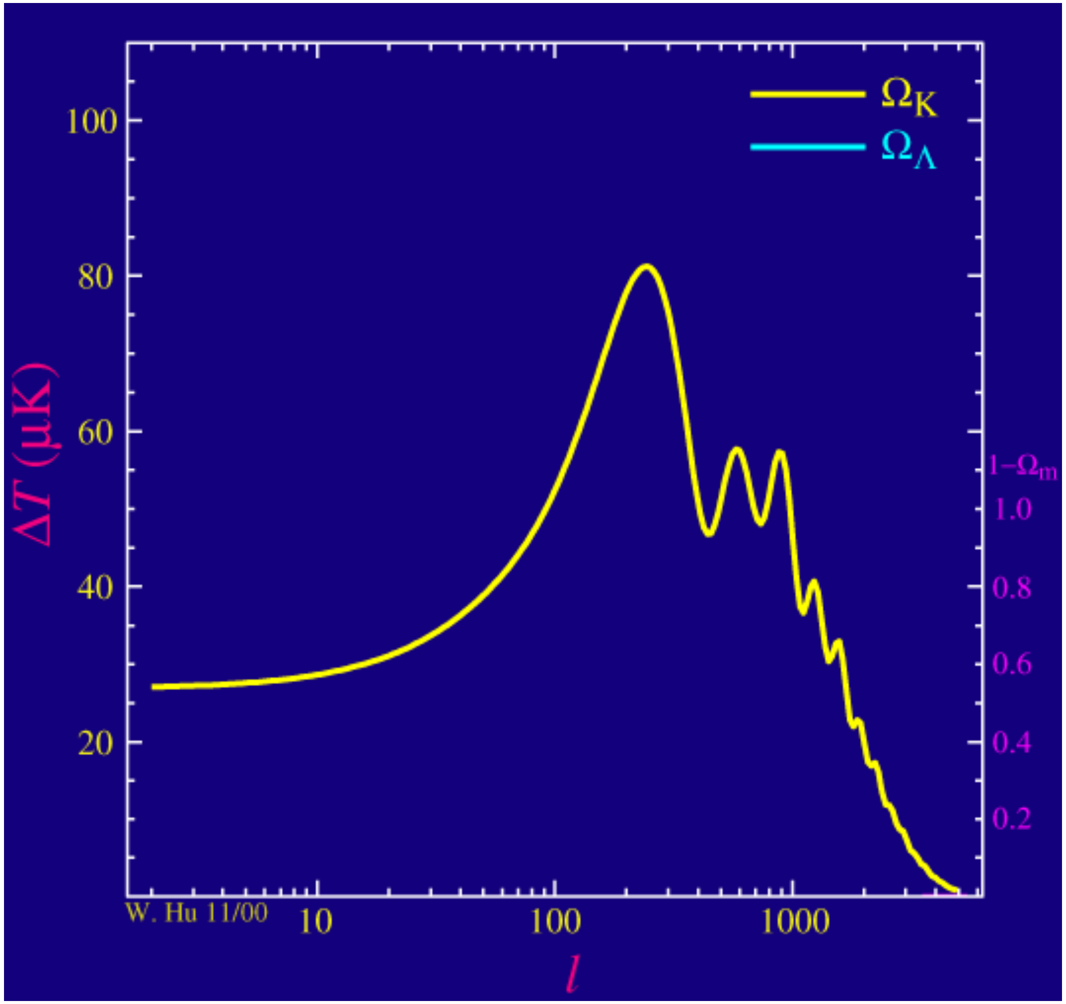
Addison et al. (2012)

What can we learn from the CMB?



First peak

http://background.uchicago.edu/~whu/intermediate/intermediate.html



Courtesy: W. Hu

Peak locations

The location of the first peak shows that the universe is close to spatially flat.

The location of the second peak, at a position that is a harmonic of the first peak, is important evidence that we are seeing sound waves from gravitational potential perturbations originating in the early universe.

The relative amplitude of the second peak provides information on the amount of baryons.

Peak heights

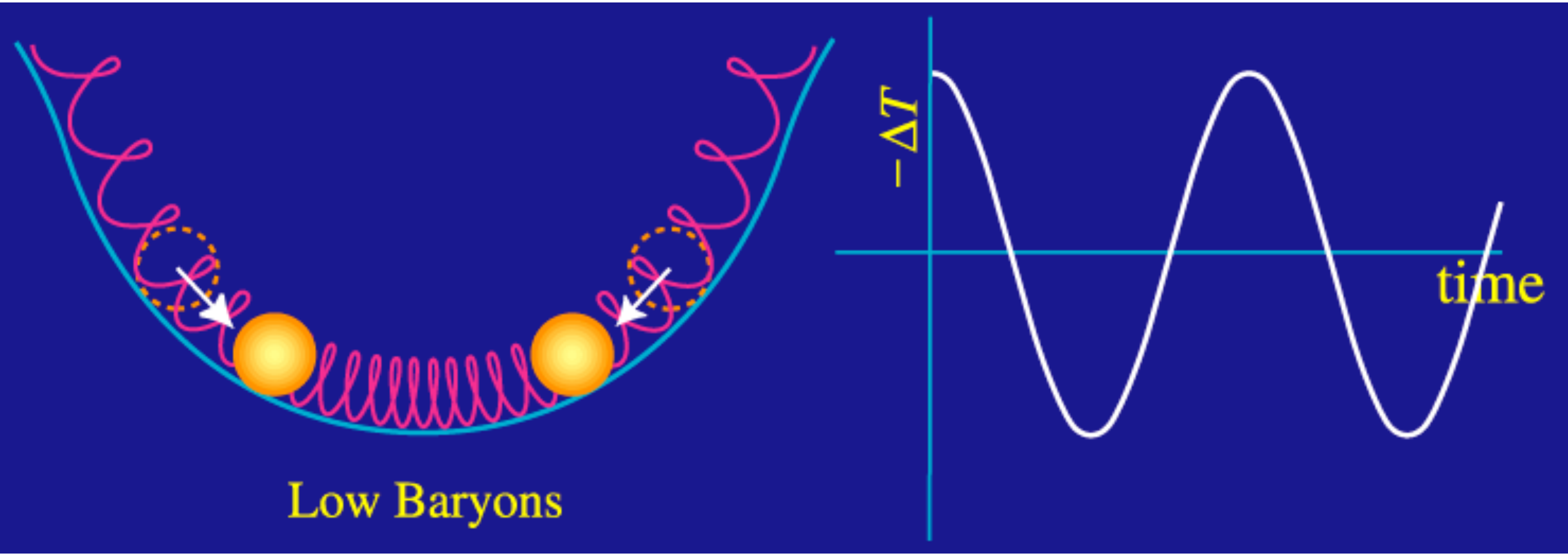
Since the odd numbered (first, third, fifth...) acoustic peaks are associated with how far the plasma "falls" into gravitational potential wells (how much the plasma compresses), they are enhanced by an increase in the amount of baryons in the universe.

The even numbered peaks (second, fourth, sixth) are associated with how far the plasma "rebounds”.

Thus with the addition of baryons the odd peaks are enhanced over the even peaks. For example, baryons make the first acoustic peak much larger than the second. The more baryons the more the second peak is *relatively* suppressed.

Peak heights

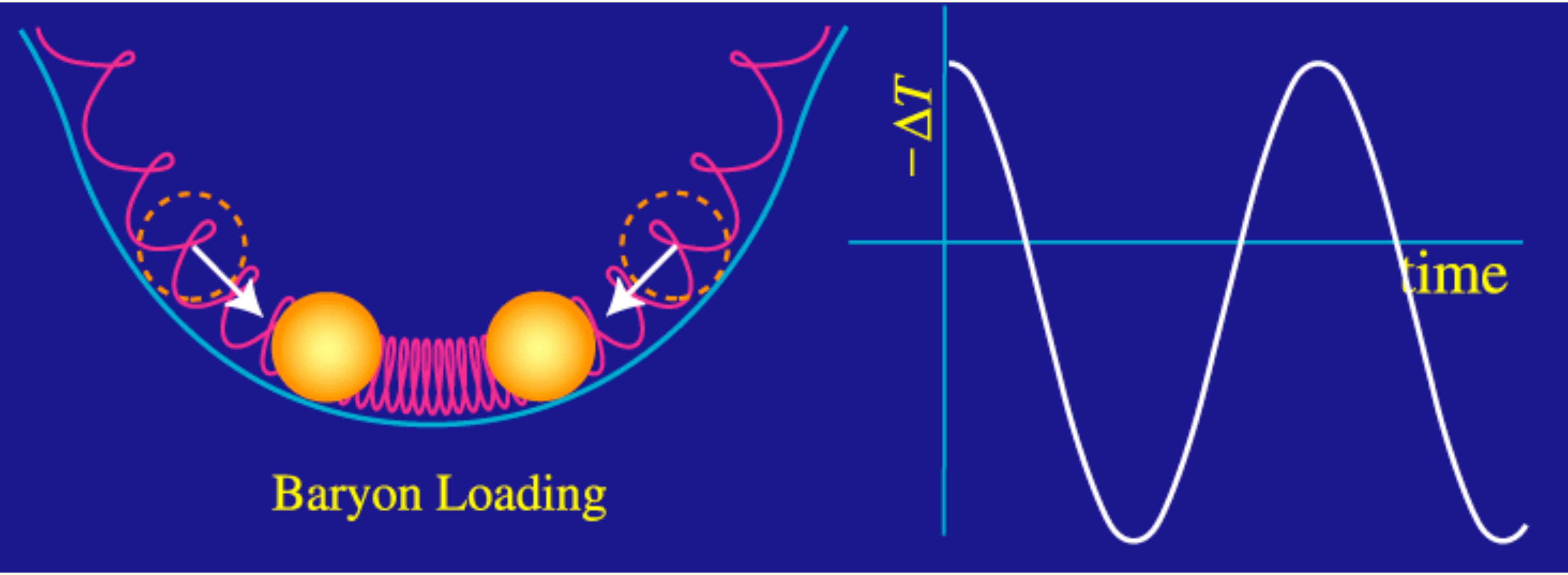
Courtesy: W. Hu



If the baryons contribute a negligible amount of mass to the plasma, the CMB temperature at the bottom of the potential well oscillates symmetrically around zero.

Peak heights

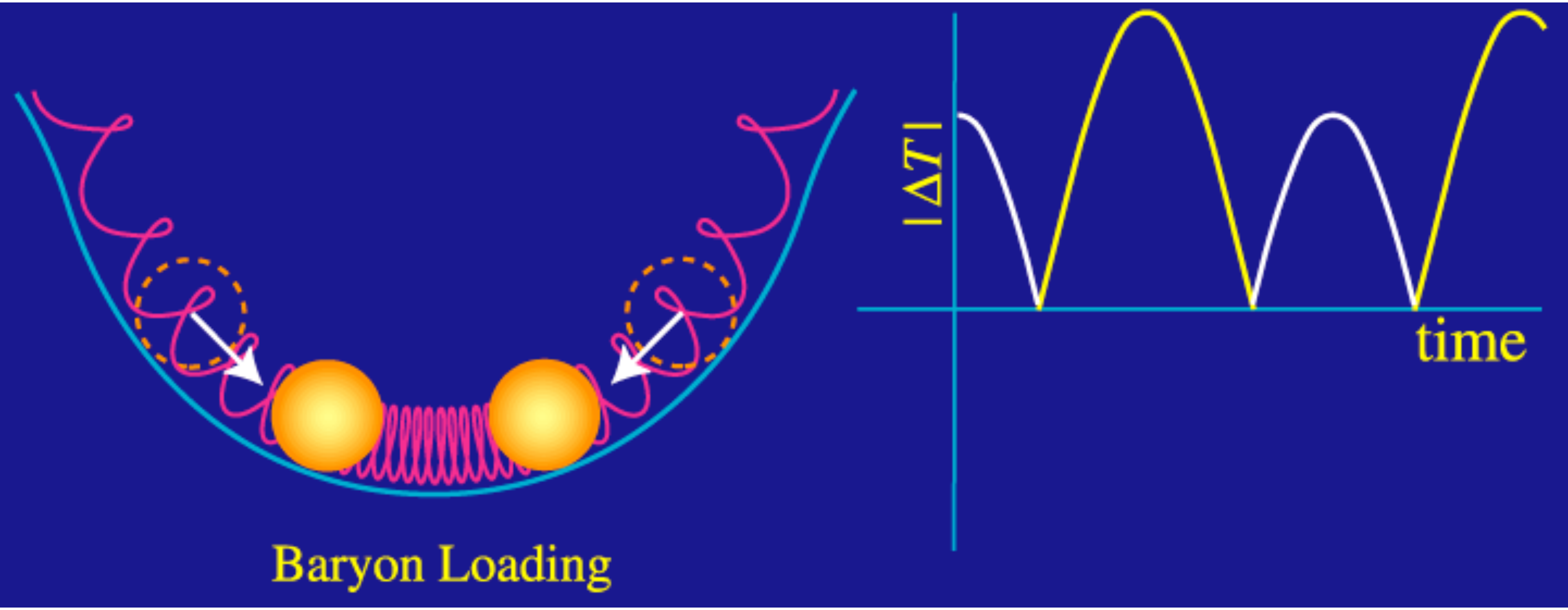
Courtesy: W. Hu



With more baryons in the system, the plasma is loaded down. The plasma compresses further inside the potential well before pressure can reverse the motion. The oscillation is now asymmetric in that the extrema that represent compressions inside potential wells are increased over those that represent rarefactions

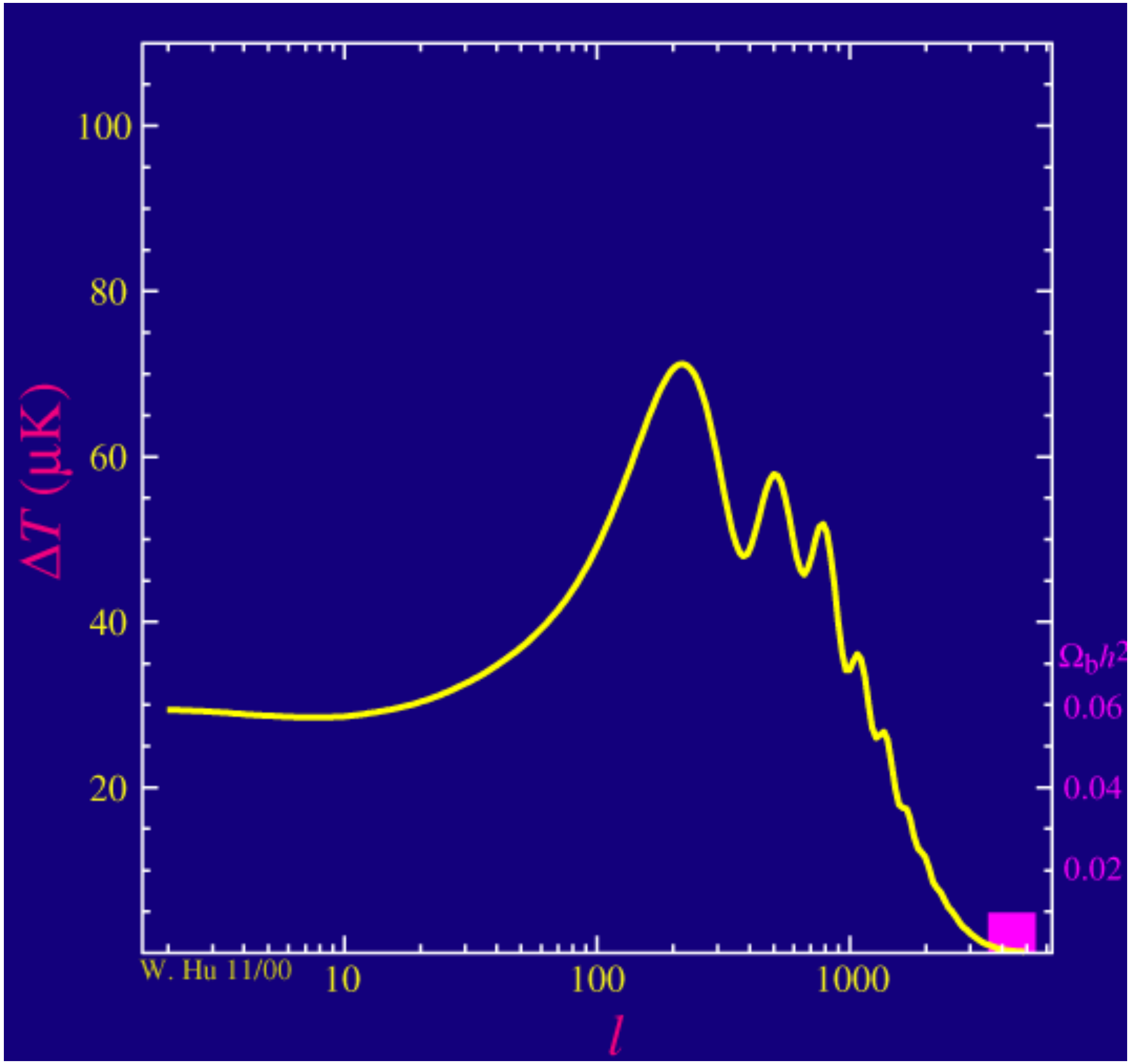
Peak heights

Courtesy: W. Hu



The power is determined by the absolute value of the temperature fluctuation: the first and third peaks are enhanced over the second peak.

Peak heights



Courtesy: W. Hu

Baryon density

The presence of baryons decreases the frequency of the oscillation, which pushes the peaks to higher multipoles.

The damping of the sound waves is also affected by the baryons and therefore the drop of the power spectrum at high multipoles is modified.

The combination of effects that baryons have on the power spectrum make this a quantity that is well measured with CMB observations.

Higher peaks

The peaks at high multipoles started oscillating when the universe was in the radiation dominated phase.

If the radiation dominates the density and is the main contributor to the gravitational potential, then once the increase in pressure stops the compression, the density fluctuation stabilizes and the gravitational potential decays with the expansion of the universe.

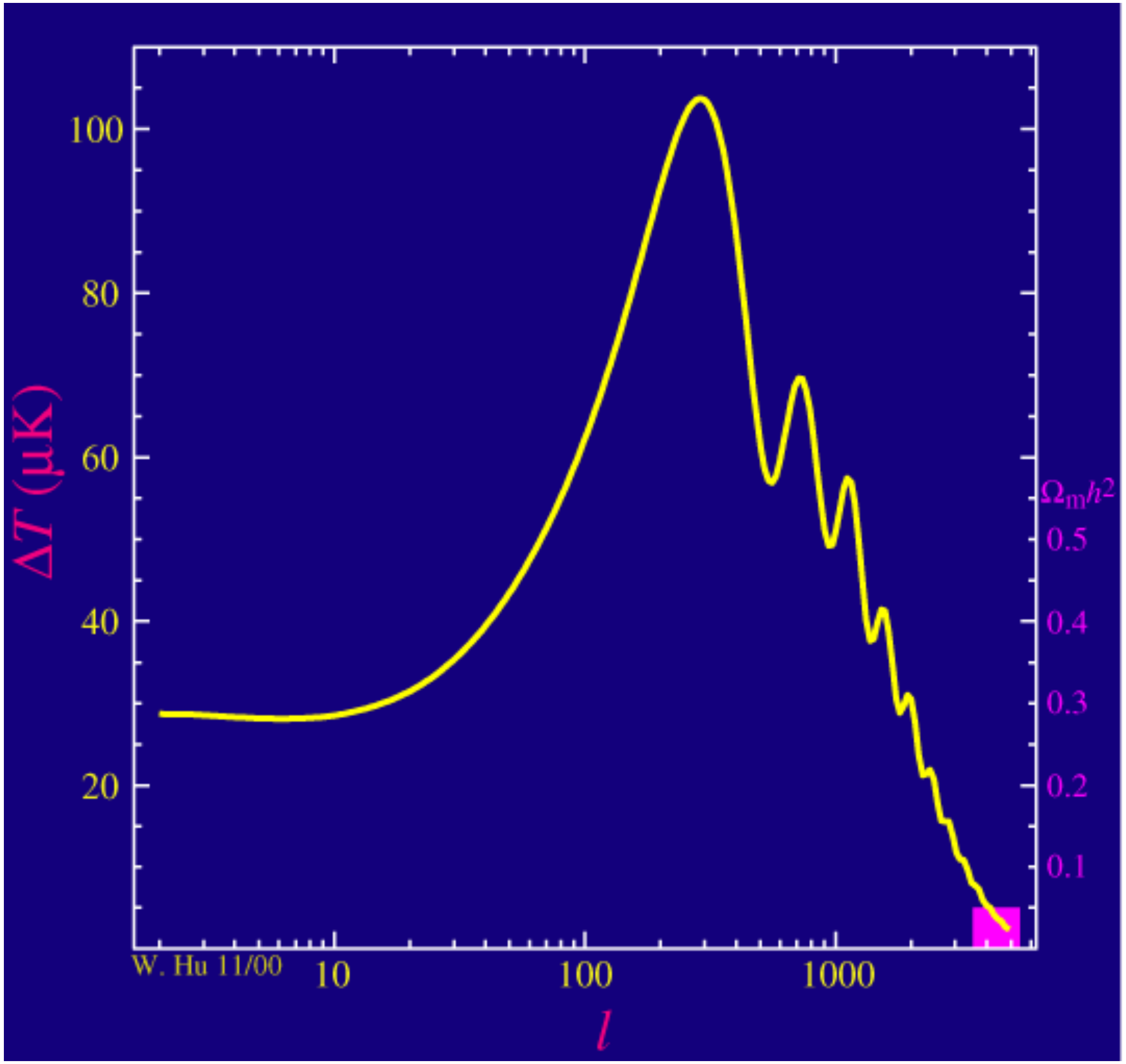
This happens when the fluid is most compressed and as it rebounds it does not fight against the gravitational potential and the oscillation is enhanced significantly.

Higher peaks

This driving effect does not occur when the density is dominated by dark matter. This is the case for peaks at lower multipoles, which started oscillating later, when the Universe was matter dominated.

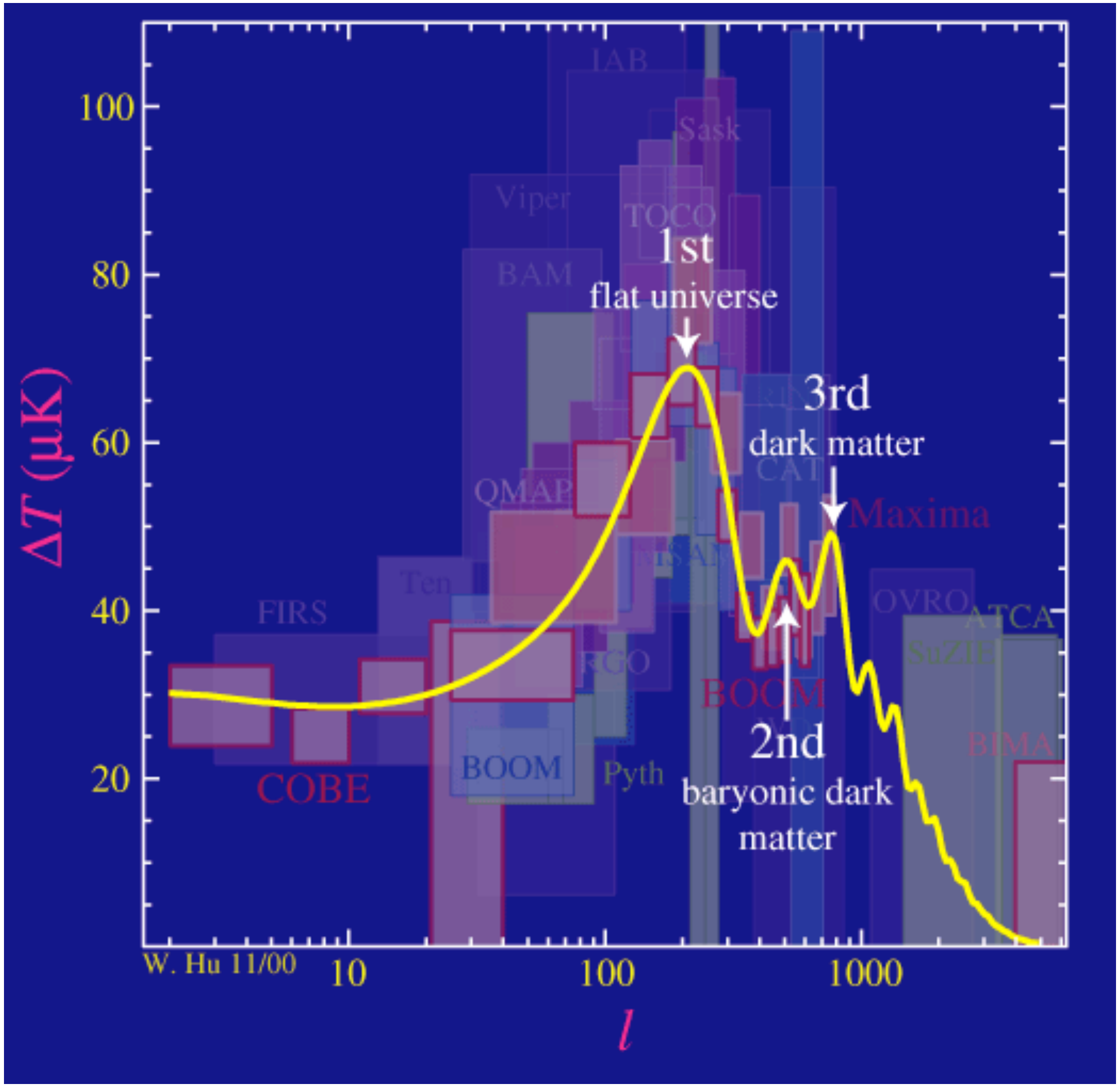
We expect to see an increase in the amplitude towards higher multipoles: the transition provides a constraint on the ratio of the energy density of (dark) matter and that of radiation.

Higher peaks



Courtesy: W. Hu

Need multiple peaks



Silk damping

Even before recombination the matter and radiation of not perfectly coupled: radiation leaks out of the perturbations, which leads to dissipation of the perturbations.

On the scale of the photon mean free path hot and cold photons can mix and temperature fluctuations on those scales are damped exponentially.

The scale where this occurs depends on t_{eq} as λ_D evolves as $(1+z)^{-5/2}$ before t_{eq}, $(1+z)^{-9/2}$ after t_{eq}.

At t_{rec} the corresponding mass $M_D=10^{12}(\Omega h^2)^{-5/4}\ M_{sun}$, which corresponds to a cluster-scale fluctuation.

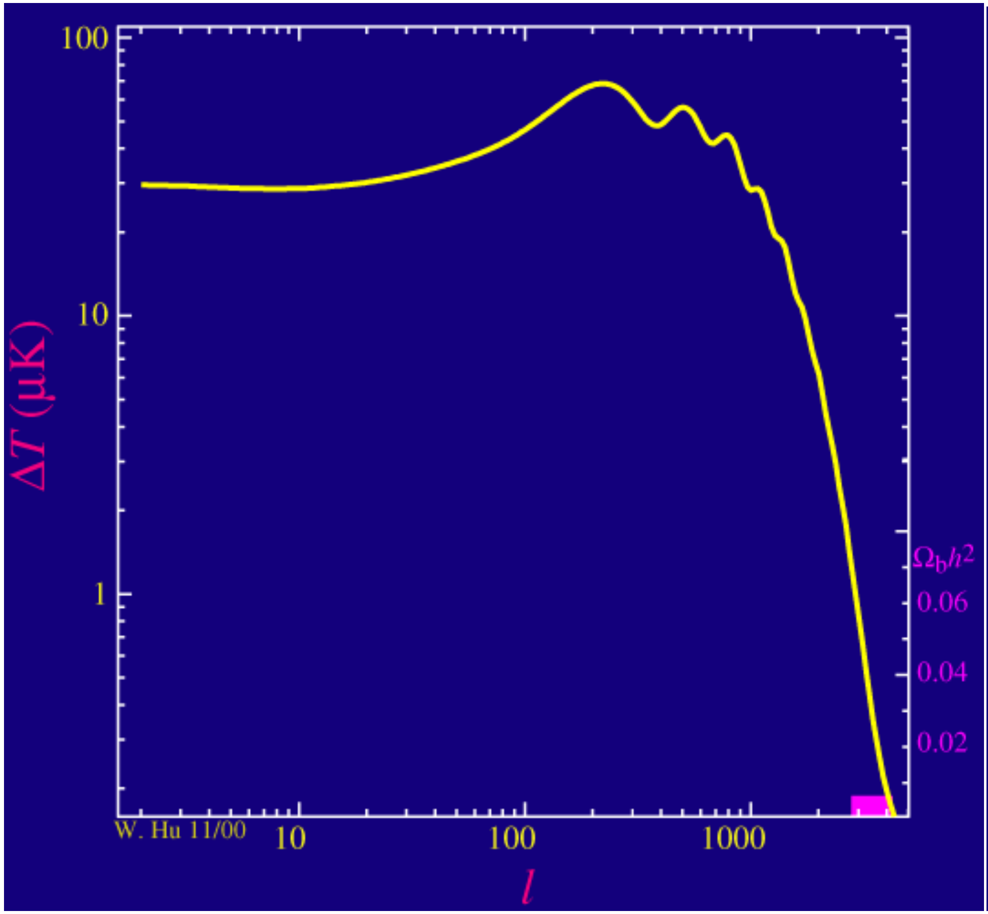
Silk damping

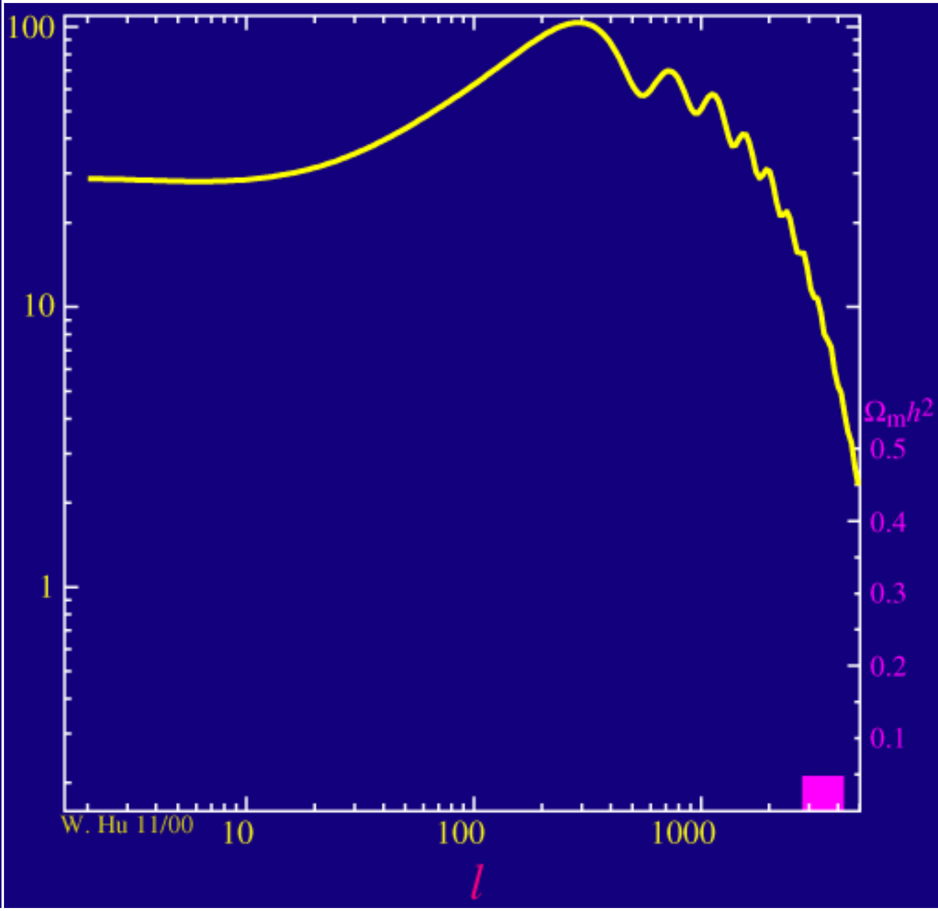
The damping depends on the mean free path of the photons and thus on the baryon density: a higher density moves damping to higher multipoles

The distance also depends on the density at recombination, and thus on t_{rec}, which is largely determined by the dark matter density: a higher matter density shifts damping to lower multipoles.

This gives consistency checks with the information inferred from the peaks, but also allows us to test the physics of recombination.

Silk damping





Constraints on parameters

Comparison of *Planck*-only and *WMAP*-only Six-Parameter ΛCDM Fits[a]

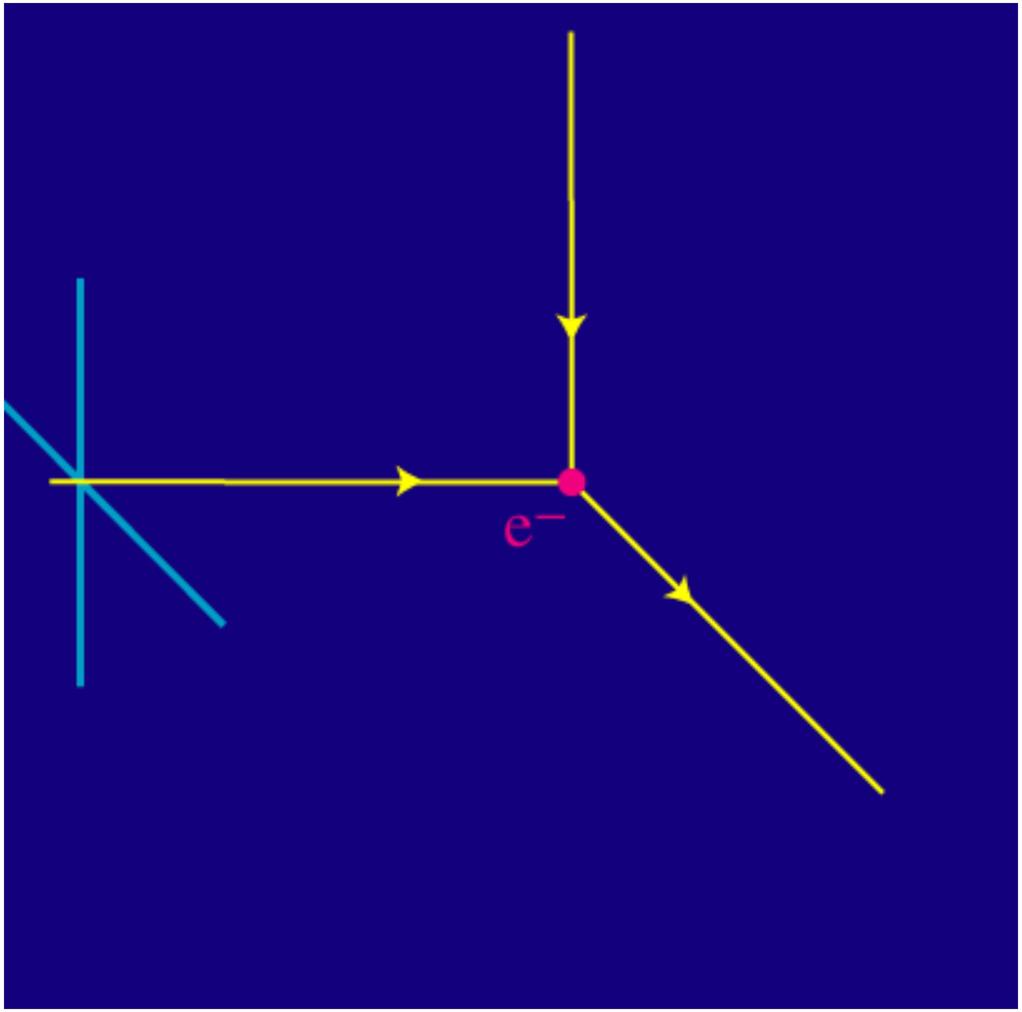
Parameter	*Planck* ("CMB+Lens")	*WMAP* (9-year)	Difference value	Difference *WMAP* σ
$\Omega_b h^2$	0.02217 ± 0.00033	0.02264 ± 0.00050	-0.00047	0.9
$\Omega_c h^2$	0.1186 ± 0.0031	0.1138 ± 0.0045	0.0048	1.1
Ω_Λ	0.693 ± 0.019	0.721 ± 0.025	-0.028	1.1
τ	0.089 ± 0.032	0.089 ± 0.014	0	0
t_0 (Gyr)	13.796 ± 0.058	13.74 ± 0.11	56 Myr	0.5
H_0 (km s^{-1}Mpc^{-1})	67.9 ± 1.5	70.0 ± 2.2	-2.1	1.0
σ_8	0.823 ± 0.018	0.821 ± 0.023	0.002	0.1
Ω_b	0.0481[b]	0.0463 ± 0.0024	0.0018	0.7
Ω_c	0.257[b]	0.233 ± 0.023	0.024	1.0

[a]The new *Planck* results strongly favor the standard six-parameter ΛCDM model with parameter values that are consistent with *WMAP* parameters, as shown in this table which compares results derived entirely from *Planck* data with those derived entirely from *WMAP* data.

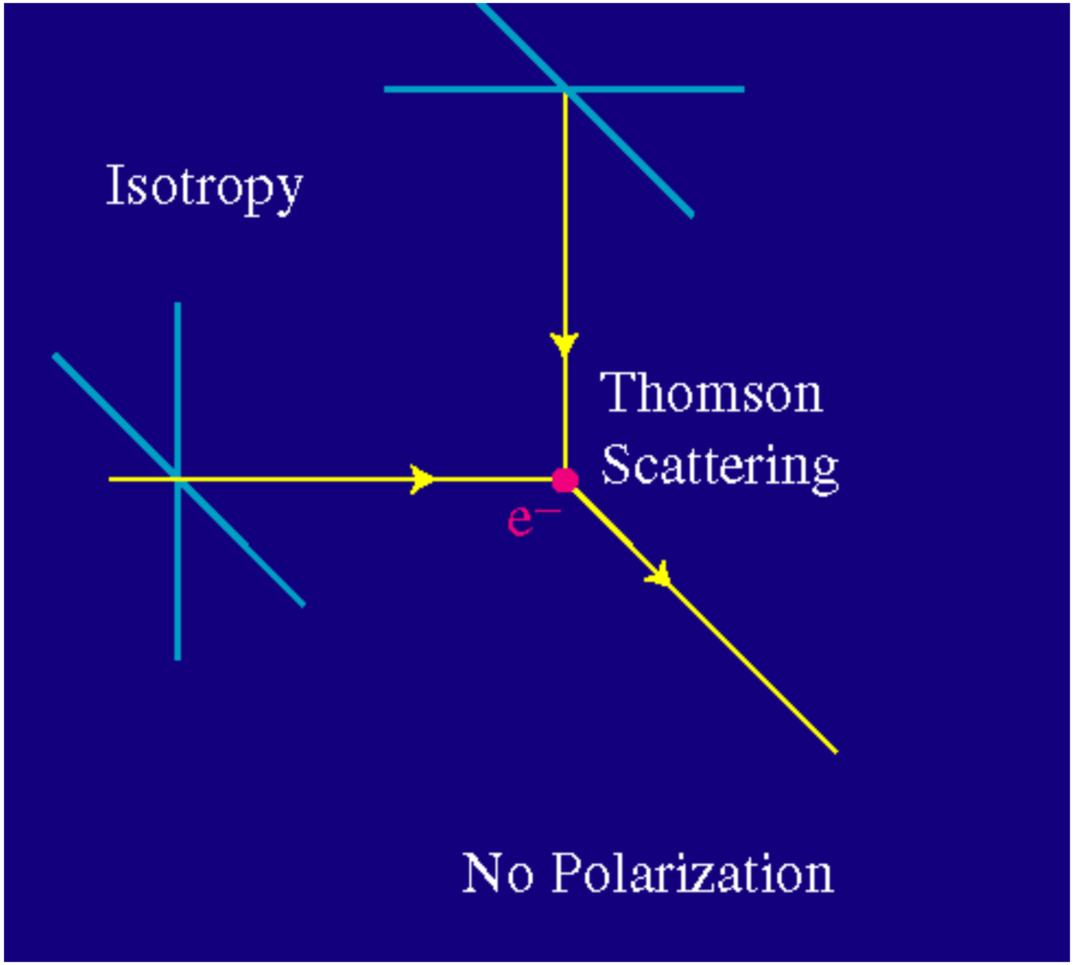
[b]Parameters derived from quoted values. No error estimate is given for this data/model combination.

Planck collaboration

CMB polarization

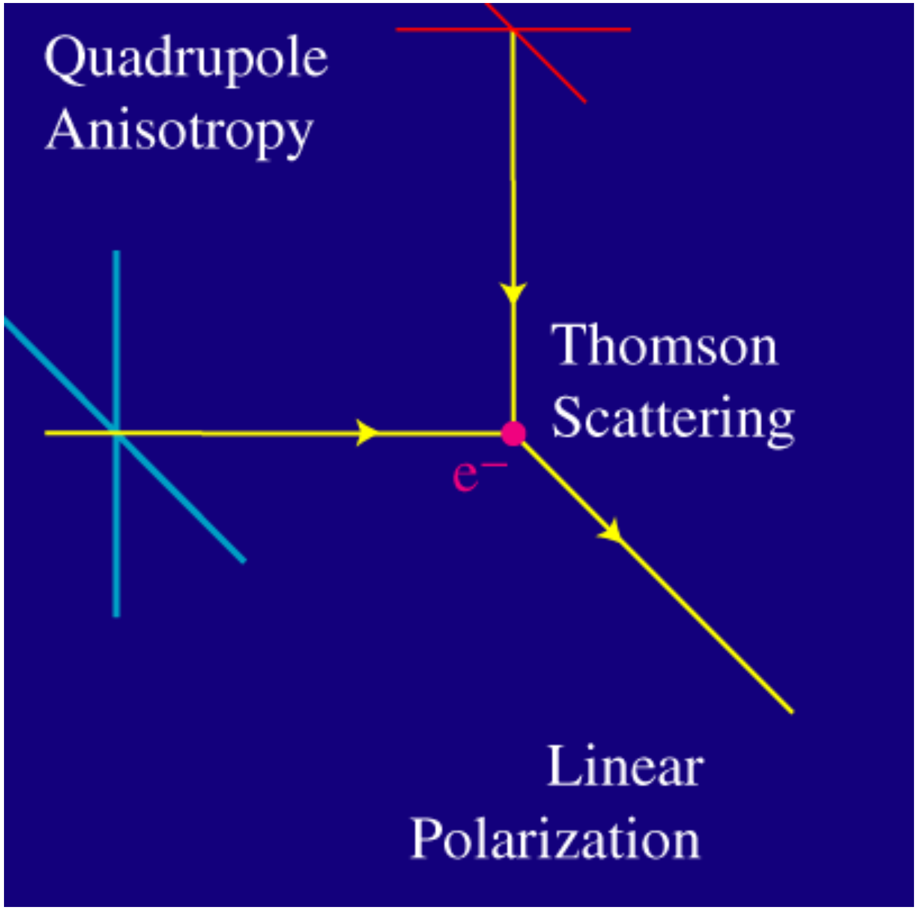


CMB polarization



If the radiation is isotropic then there is no net polarization

CMB polarization



We observe a linear polarization that is aligned with the cold axis of the quadrupole anisotropy

CMB polarization

When photons from different temperature regions meet, a temperature inhomogeneity is converted into an anisotropy. Scattering reduces the level of anisotropy in the radiation exponentially (similar to what we saw for Silk damping).

Only at the end of recombination can a quadrupole in the radiation field form by the diffusion of photons in and out of regions with different temperatures. This can only occur on small scales: we expect a sharp decline in the power spectrum of the polarization on large scales.

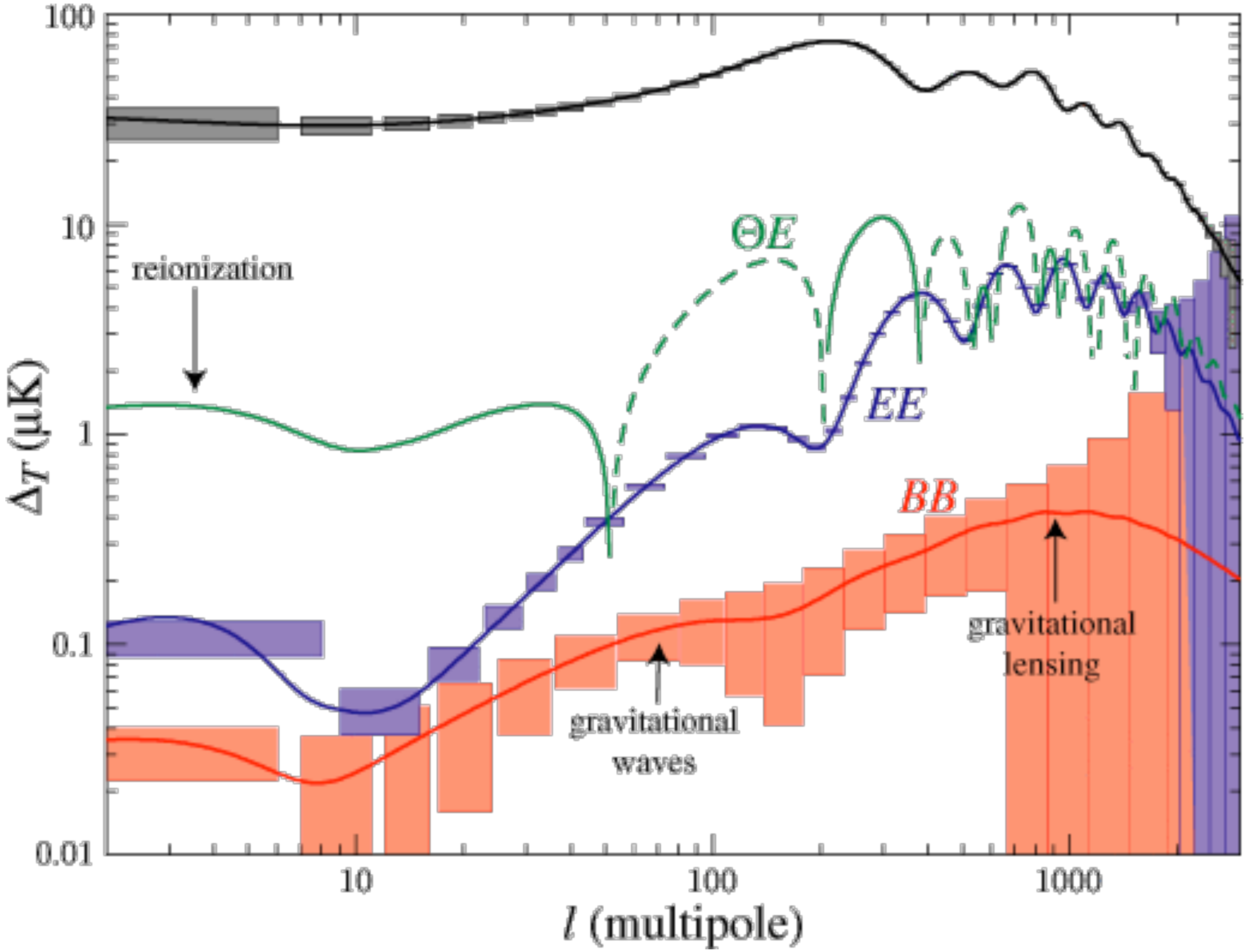
CMB polarization

The polarization power peaks near the diffusion scale, $l \approx 1000$
The level of polarization is <10%, and the amplitude is at the 1 part per million level (micro Kelvin)

There is a second peak on large angular scales at the 1 part per 10 million level (tenth of micro Kelvin) which is caused by the fact that hydrogen was reionized.

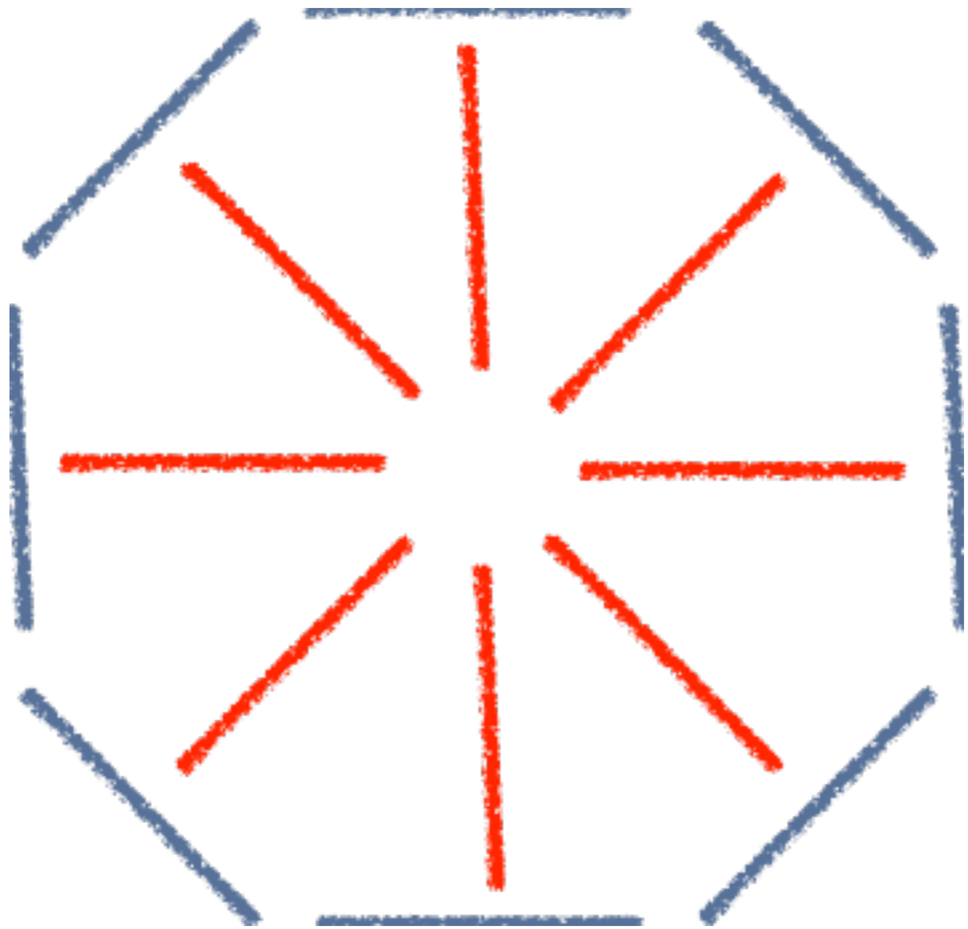
The peaks in the polarization power spectrum track the acoustic velocity and are out of phase with the temperature peaks.

CMB polarization

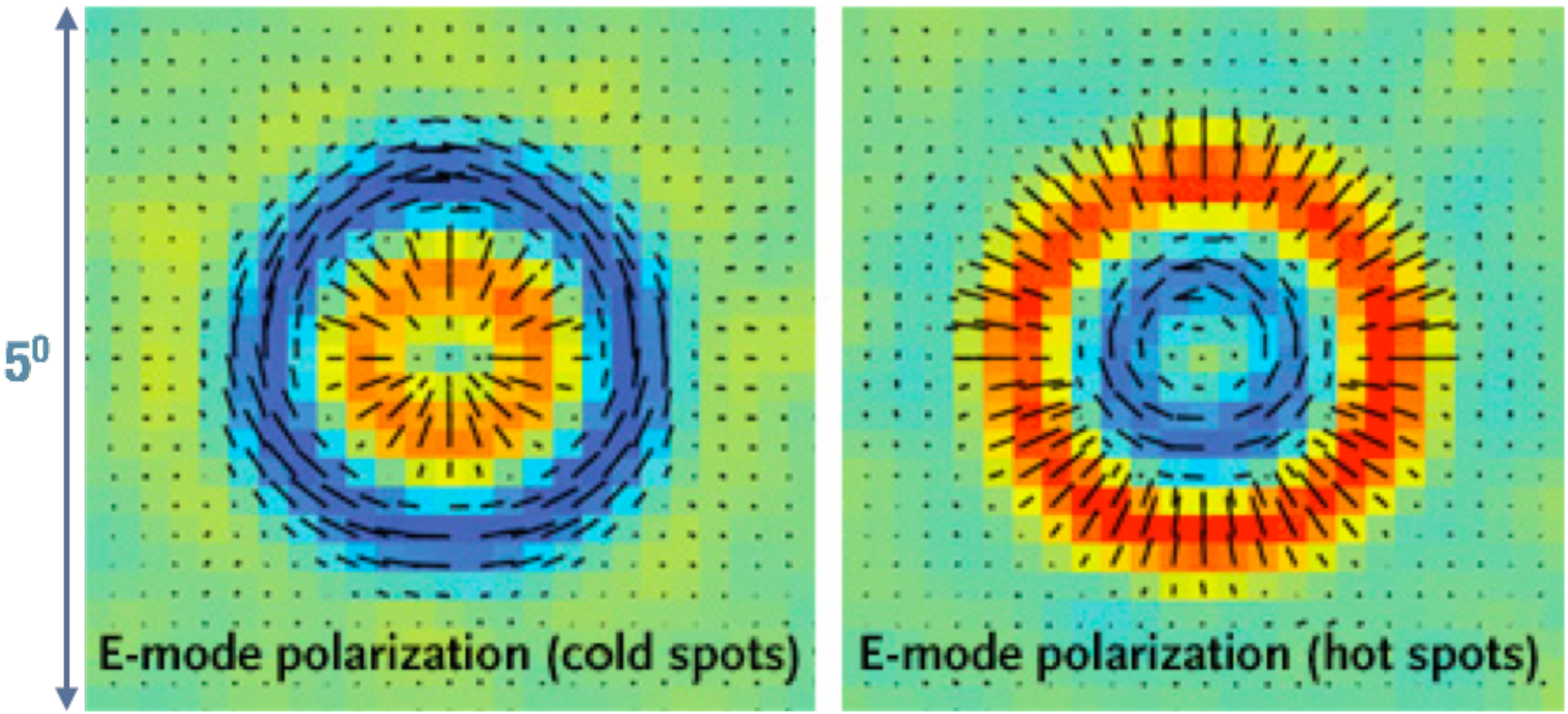


Hu & Dodelson (2002)

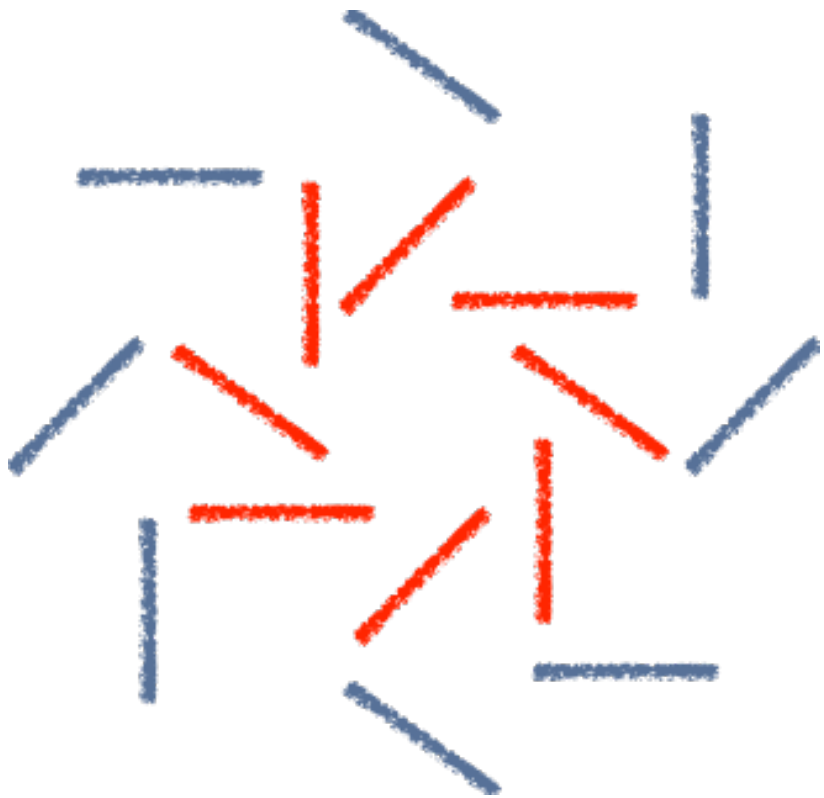
CMB polarization patterns



CMB polarization patterns

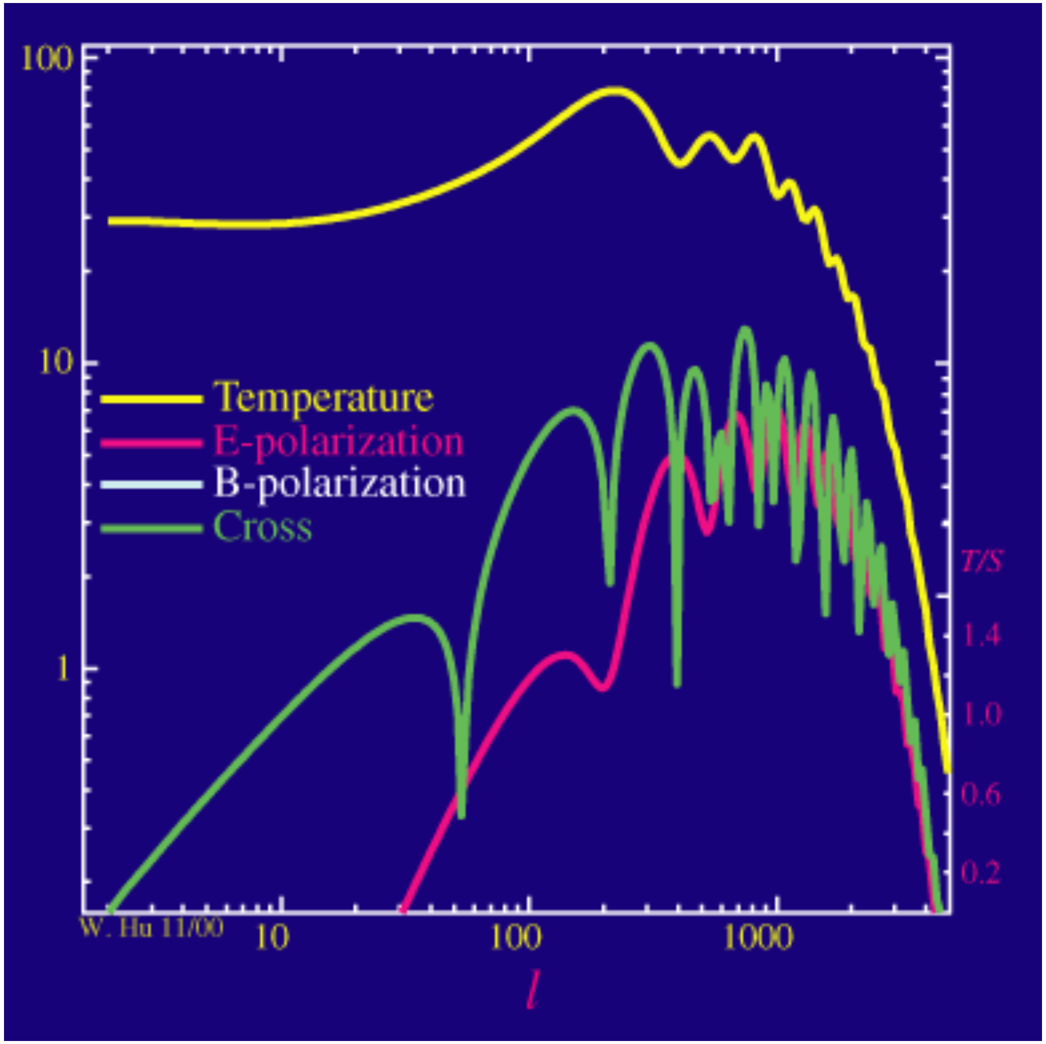


CMB polarization patterns



B-mode patterns are the best way to test another prediction from inflation: there are gravity waves (but no clear prediction about the amplitude)

CMB polarization patterns

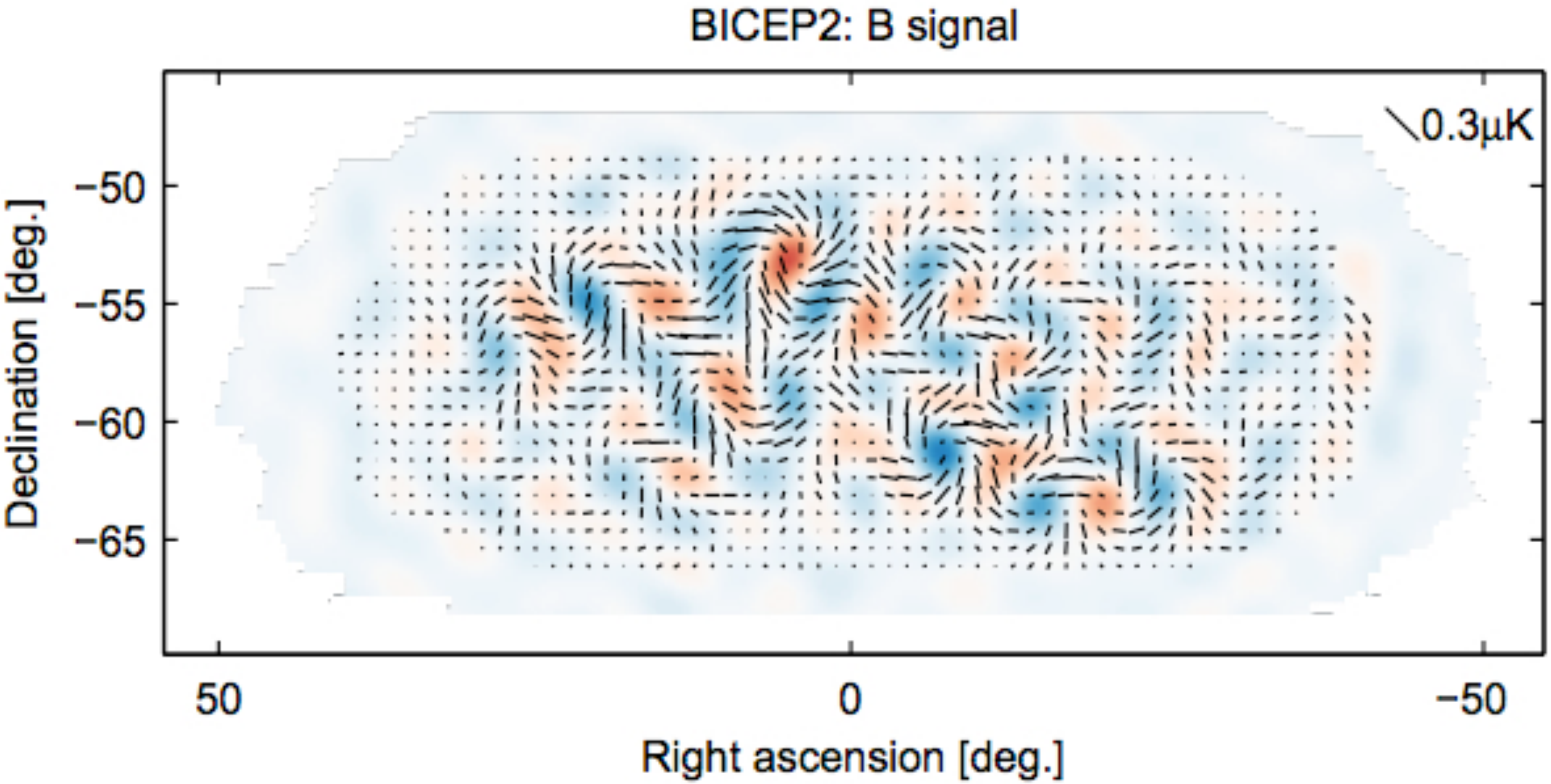


Difficult to measure

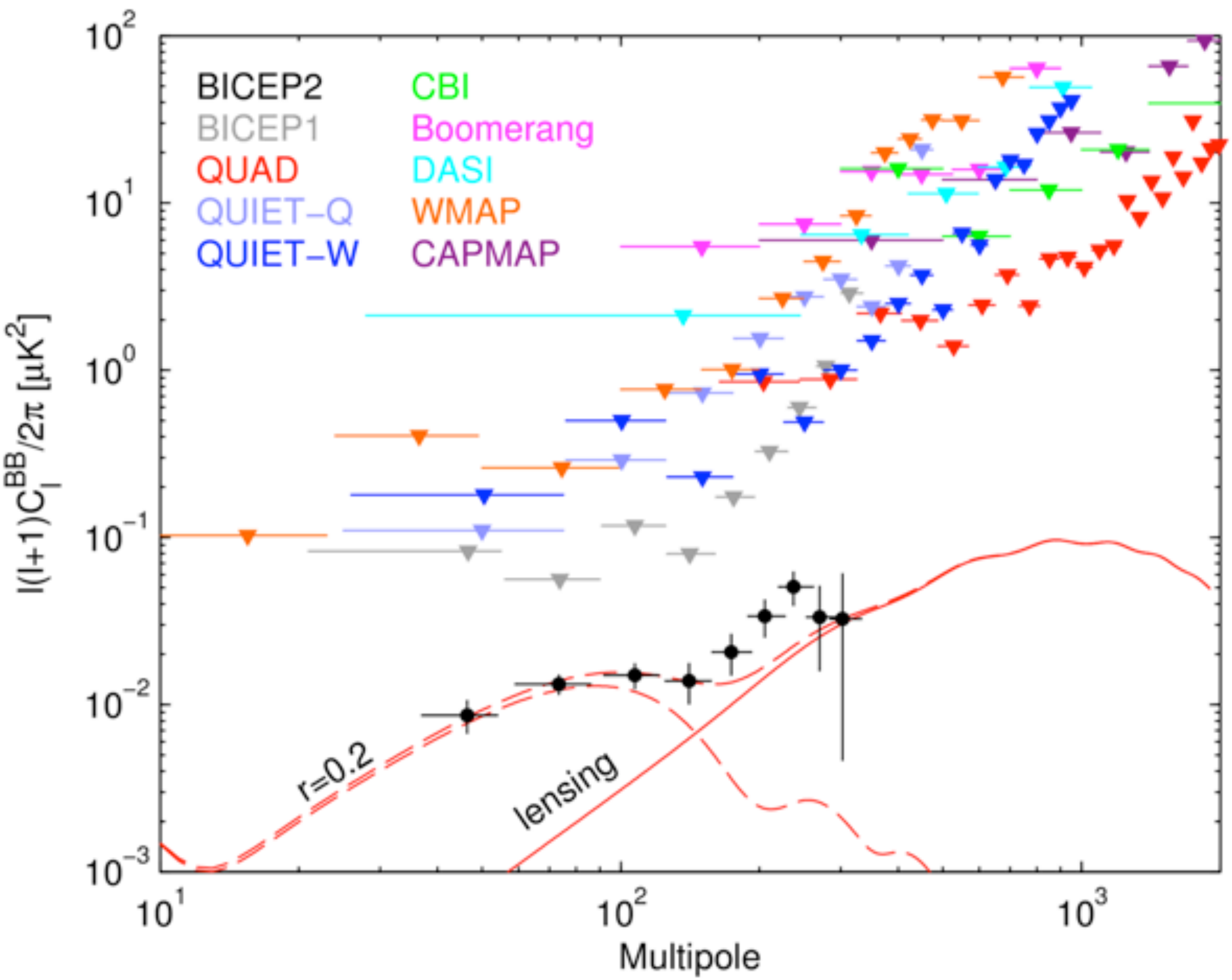
The South Pole is one of the best (=driest) places on Earth and best suited for such experiments. Space is of course better…

Difficult to measure

B-modes measured?



BICEP2 results



Many open questions in cosmology

- What is the nature of dark energy?
- What is the nature of dark matter?
- Did inflation occur?
- Can we learn more about high energy physics?

Of course the early Universe has left it imprint on the observable Universe, providing the seeds for structure and galaxy formation.