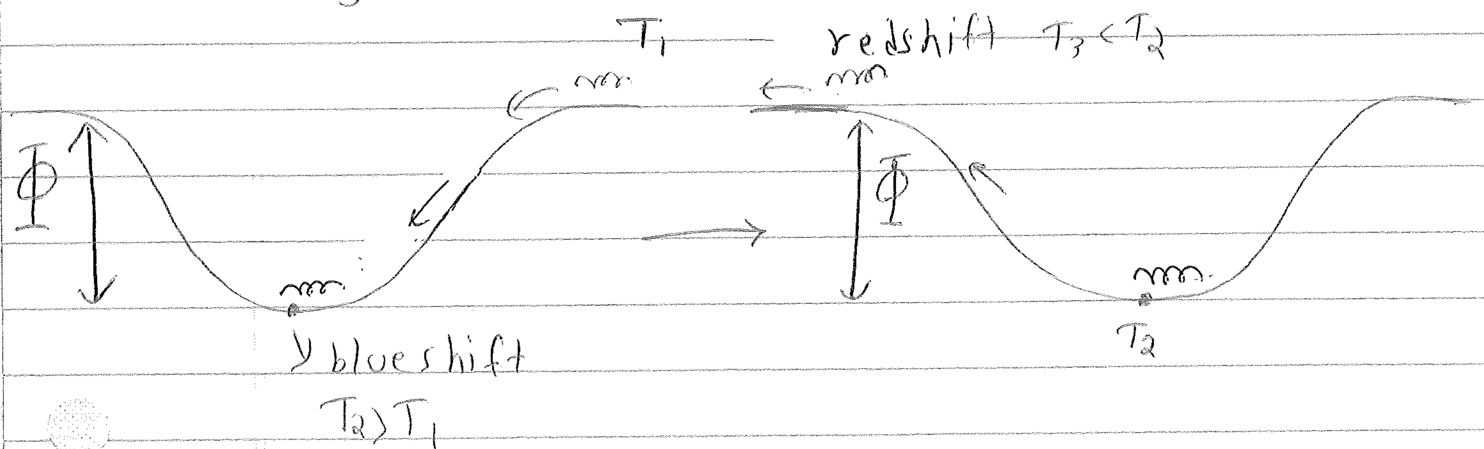
Lec 28: 12/02/2013

Cosmic Microwave Background (Cont'd):

After their last scattering off free electrons at the time of recombination, CMB photons move freely. While traveling toward us, they go through many potential wells and hills associated with (evolving) structures of different size. As long as these potential wells are time-independent, their net effect on the temperature of CMB photons will vanish. This can be understood as a photon is blueshifted when going to the bottom of a potential well, and is redshifted when climbing out of it:



$T_2 - T_1 = \Phi$ (blueshift) , $T_3 - T_2 = -\Phi$ (redshift) $\Rightarrow T_1 = T_3$

The situation, however, changes if photons travel through a potential well (or height) that varies in time. In this case, depending on the change in $\Phi_{(t)}$, the temperature of the photon can undergo a net increase or decrease. There will therefore be a net blueshift or redshift associated with time-dependent potential wells. This is the so-called "Integrated Sachs-Wolfe (ISW) effect because it goes as $\int_{t_{in}}^{t_{out}} \dot{\Phi}_{(t)}\, dt$, where t_{in} and t_{out} denote the times when photon entered and exit the potential well respectively.

To be more precise, one can show that the net effect on the photon temperature due to the ISW is $2\Delta\Phi$, where $\Delta\Phi$ is the change in the potential felt by the photon due to the explicit time variation $\dot{\Phi} \neq 0$.

The question is when during their journey the photons that are traveling along the line of sight go through time-dependent gravitational potentials. There are two types of ISW effect on the CMB photons: early time ISW and late-time ISW. Here we discuss them in more detail.

Eary-time ISW Effect:

Around the time of recombination t_{rec}, the contribution of radiation to the total energy density is subdominant, but it is not totally negligible. Radiation constitutes about 20% of the energy density at that time, which can be estimated by the amount of relative redshift of ρ_{rad} and ρ_m between $t_{eq} \sim 50{,}000$ yr and $t_{rec} \sim 400{,}000$ yr: $\frac{\rho_{rad}}{\rho_m} \propto a^{-1}$, $\frac{a_{rec}}{a_{eq}} \sim \left(\frac{t_{rec}}{t_{eq}}\right)^{\frac{2}{3}} \sim 4$.

As we saw before, the gravitational potential from perturbations of dark matter decay in a radiation-dominated universe. Around t_{rec}, the universe is matter-dominated, but the significant fraction of radiation implies that Φ will not be constant but rather decreases. As a result, the gravitational potential will be time dependent around t_{rec}, which will result in the ISW effect. Since this happens close to t_{rec}, it is called the "early time ISW" effect.

The question is how the early time ISW affects the CMB power spectrum, speifically, what perturbation modes will be affected by it most. The decrease in the gravitational potential occurs when a mode enters the horizon. Those perturbations that are well outside the horizon at t_{rec} (i.e., $\ell \ll 100$) will not be affected by the early time ISW. Their gravitational potential is essentially constant as long as they are outside the horizon. Also, the contribution from radiation has already become negligible when the become subhorizon. The early-time ISW is not important for those perturbations that are well inside the horizon at t_{rec} (i.e., essu

Late-time ISW Effect:

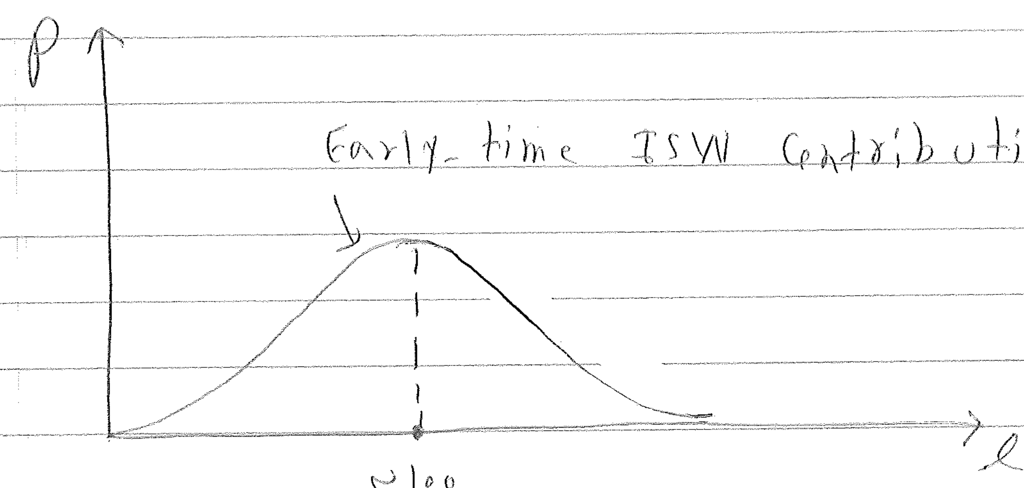
A late time variation in the gravitational potential of dark matter perturbations can arise in a universe that undergoes accelerated expansion. To demonstrate this, let us consider a universe that is dominated by cosmological constant. Recall that the gravitational potential of dark matter perturbations is:

$$\Phi \propto a^{-1}\, \delta_{DM}$$

In a matter dominated universe $\delta_{DM} \propto a$, and hence Φ is constant. In a universe dominated by cosmological constant, however perturbations cease to grow and freeze (i.e., $\delta_{DM} = $ const.). Since "a" grows exponentially in this case, then Φ decays exponentially. This rapid decay of Φ can considerably affect the photons that travel through the associated potential well (or hill).

either. The reason being that the gravitational potential of these modes has already decayed away. It started when the modes became subhorizon (happened at $t \ll t_{rec}$), at which time radiation constituted even a larger fraction of the total energy density.

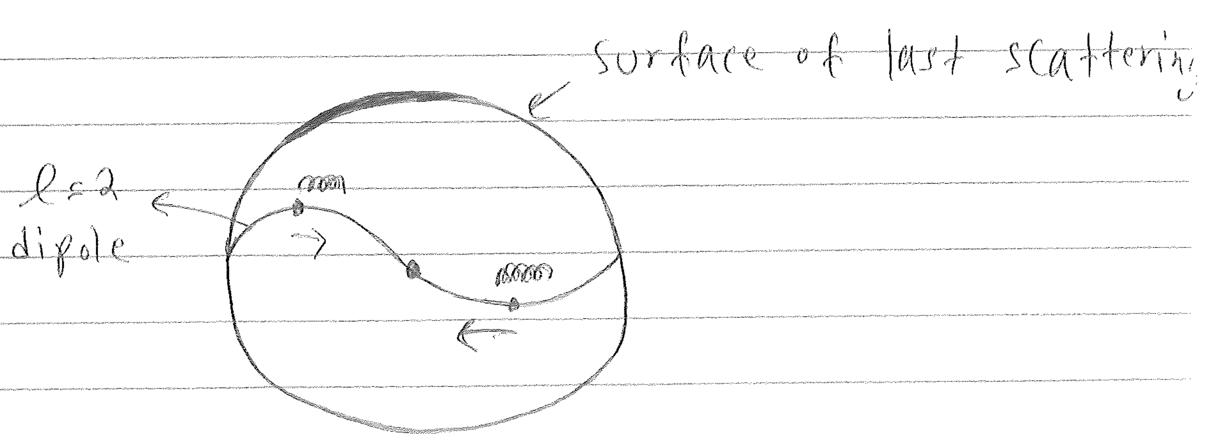
In consequence, modes that enter the horizon at $t \sim t_{rec}$ are affected most by the early-time ISW:



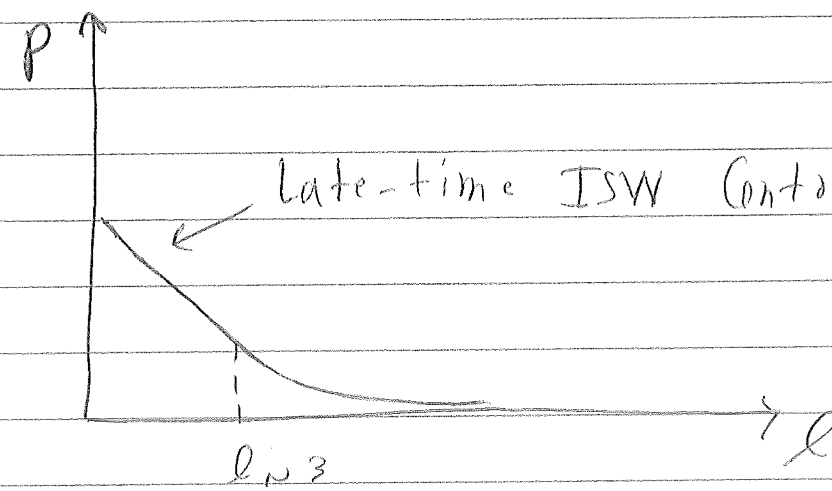
Due to its dependence on l, the early-time ISW results in a broader 1st acoustic peak in the CMB power spectrum, while not affecting other peaks.

Observations suggest that our universe has entered a period of accelerated expansion for the past few billion years. So far, all observations are consistent with a cosmological constant being the source of this accelerated expansion. The CMB photons are affected by this late variation in the gravitational potential caused by the accelerated expansion. This is the so called "late time ISW" effect.

From our discussion, it is clear that those perturbation modes in the power spectrum are affected most that whose potential undergo the most significant change during the accelerated expansion phase. These are the modes that correspond to lowest multipoles:



The late-time ISW effect therefore is most important for low multipoles ($\ell < 3$) and lifts the power spectrum in that region. Its effect becomes negligible at higher ℓ:



One comment is in order. The ordinary SW and the ISW effects refer to potentials that correspond to perturbations in the linear regime. Photons can also be redshifted or blueshifted by the time variation in the gravitational potential corresponding to perturbations in the nonlinear regime. This is called the "Rees-Sciam" effect. For example, photons that travel through a supercluster under formation can experience the Rees-Sciama effect