Lec 23: 11/13/2013

Cosmic Microwave Background (Cont'd):

Oscillatory Regime:

We now consider evolution of matter perturbations in the stable regime $\lambda < \lambda_J$. The equation for dark matter perturbations remain the same due its presurelessness:

$$\ddot{\delta}_{DM} + \frac{4}{3t}\dot{\delta}_{DM} - \frac{2}{3t^2}\left(\varepsilon_{DM}\delta_{DM} + \varepsilon_B\delta_B\right) = 0$$

δ_{DM} then just keeps growing $\propto t^{2/3}$ in the matter dominated regime.

The equation for baryon perturbation, however, now includes the pressure term:

$$\ddot{\delta}_B + \frac{4}{3t}\dot{\delta}_B + \frac{k^2}{3t^{4/3}}\delta_B = \frac{2}{3t^2}\varepsilon_{DM}\delta_{DM} \qquad (\mathrm{I})$$

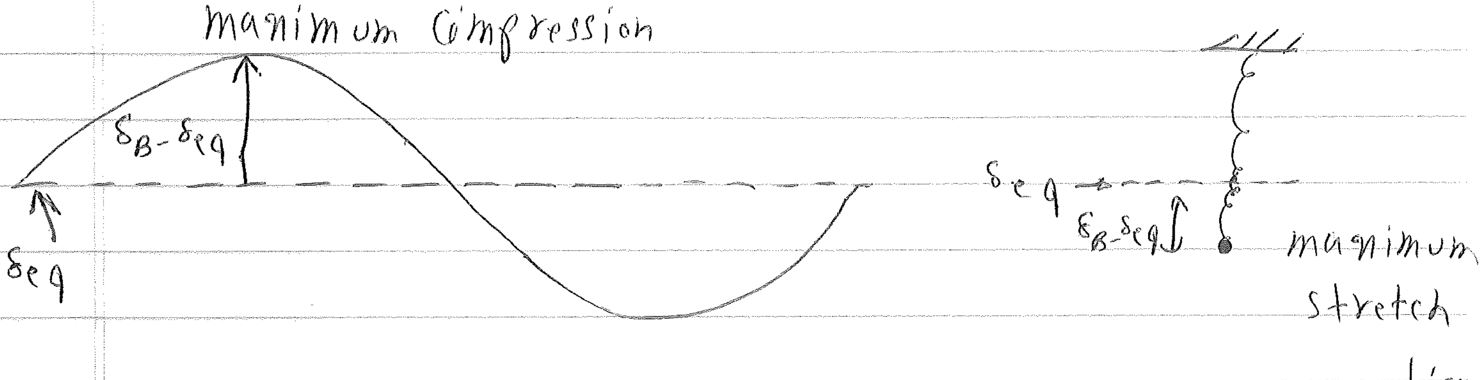
Here we have neglected the term $\frac{-2\varepsilon_B}{3t^2}\delta_B$, which is subdominant for $\lambda < \lambda_J$. Eq. (I) is that of a simple harmonic oscillator in the presence of an external force. The external force is provided by dark matter perturbations δ_{DM}. Parameters of the oscillator (such as its frequency and damping) are time dependent, but their variation is much smaller than the period of oscillations. The oscillator oscillates about its equilibrium point, which is given by:

$$\delta_{eq} = \frac{\frac{2}{3t^2} \epsilon_{DM} \delta_{DM}}{\frac{k^2}{3+\frac{4}{3}}}$$

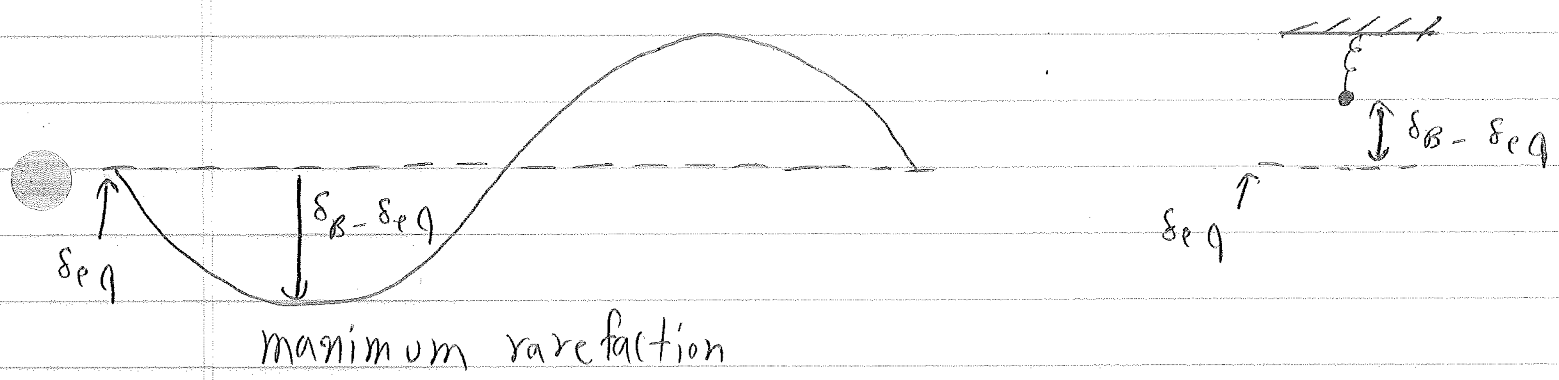
Considering that $\delta_{DM} \propto t^{\frac{2}{3}}$, we see that δ_{eq} is a constant (in the matter-dominated phase). Eq. (I) can then be rewritten as:

$$(\ddot{\delta_B - \delta_{eq}}) + \frac{4}{3t^2}(\dot{\delta_B - \delta_{eq}}) + \frac{k^2}{3+\frac{4}{3}}(\delta_B - \delta_{eq}) = 0 \qquad (\text{II})$$

Using the harmonic oscillator analogy, we can find a correspondence between compression / rarefaction of the baryon-photon fluid and extrema in the position of the oscillator. The maximum compression of the fluid occurs at the end of unstable regime ($\lambda > \lambda_J$), which corresponds to the maximum stretch of the oscillator;



Half a period later, the fluid is rarefied maximally (relative to the equilibrium point):



The oscillations continue implying a second compression, second rarefaction, etc. There is a damping due to the expansion of the universe, see Eq. (II), which results in a decrease in the amplitude of oscillations. We note that compression in one region is accompanied by rarefaction in another region (separated by half a wavelength). We therefore have a standing wave in in the fluid, whose dynamics is well described by that of a damped harmonic oscillator in an external field. As we will see later, the first compression corresponds to the first peak in the CMB power spectrum, the first rarefaction corresponds to the second peak in the CMB power spectrum, the second compression corresponds to the third peak in the CMB power spectrum, etc.

We will discuss the steps to go from acoustic oscillations in the baryon-photon fluid to the CMB power spectrum and various physical effects that are involved later on. For the moment, let us have a qualitative discussion of the first three acoustic peaks and the information that we can gain from them.

(1) First acoustic peak: As mentioned, it corresponds to the first compression in the baryon-photon fluid. This happens at the end of unstable regime when wavelength of the perturbation

is about the size of sound horizon. Since this length scale is know at the time of recombination, the angular diameter of the 1st peak can be used to determine the geometry of the universe (i.e., whether it is flat, open, or closed). This was first done after BOOMERANG and MAXIMA experiments provided data in early 2000's, which was in agreement with a spatially flat universe.

$\boxed{\text{First Acoustic Peak} \rightarrow \text{Geometry}}$

(2) Second acoustic peak: This peak corresponds to the perturbation mode that is at its first rarefaction at the time of recombination. As mentioned, oscillations of the baryon-photon fluid occurs in the presence of the external force provided by dark matter perturbations. Due to the lack of pressure, they do not oscillate. As a result, δ_{DM} and δ_B are in phase for the odd-number

acoustic peaks, while they are out of phase even number acoustic peaks. Intuitively, gravity of baryon perturbations interfere constructively for the odd-number peaks, while interference is destructive in the case of the even number peaks. This implies the suppression of the even number peaks relative to the odd number peaks, notably lowering the ratio of the 2nd peak to the 1st peak.

In fact, a rather small 2nd acoustic peak from the BOOMERANG and MAXIMA data led to the suggestion of a large Ω_B. This was not consistent with the value inferred from BBN, and hence resulted in some confusion. This has vanished by now (basically after the WMAP results).

$$\boxed{\Omega_B \uparrow \rightarrow \text{Suppression of Second Acoustic Peak}}$$

We will discuss this so-called "Baryon Loading" effect in more detail later on.

(3) Third acoustic peaks: This peak corresponds to the perturbation mode that underwent one full oscillation and reached its second compression at the time of recombination. This mode (and higher ones) started oscillating close to t_{eq} (or eve before that) when density of radiation was comparable to that of matter. Growth of dark matter perturbations become insignificant at this time, which results in a decrease in δ_{eq}, see Eq. (II). This has the effect of making the amplitude of oscillations larger for the 3rd and higher peaks. Such a rise in the CMB power spectrum is an indicator of the dark matter density.

$$\boxed{\Omega_{DM}\uparrow \rightarrow \text{Enhancing the Third Acoustic Peak}}$$

We will discuss this "Radiation Driving" effect in more detail later.