Cosmic Microwave Background Part 2

Recap from last time:

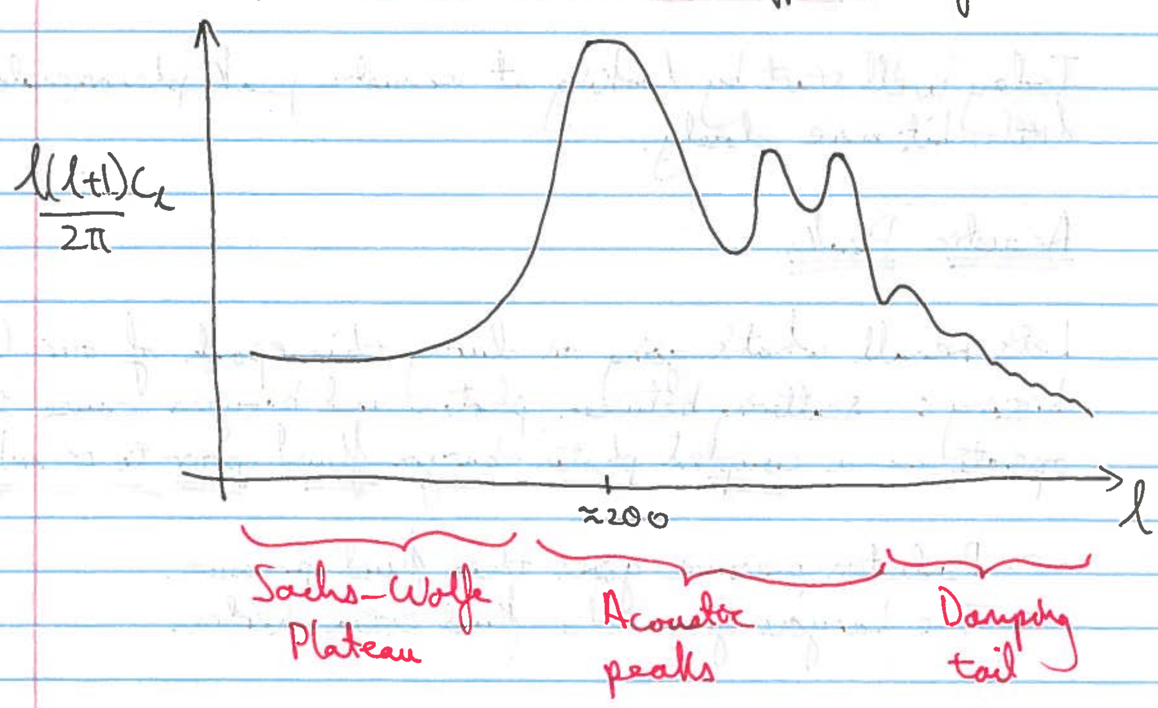
- CMB exhibits anisotropies, which are the combination of
  i) Primary fluctuations (connected to inhomogeneities)
  ii) Projection effects
  iii) Secondary effects (photons affected on their way to us).

- Capture the information content of the CMB using the angular power spectrum C_ℓ:

$$a_{\ell m} = \int d\Omega \, Y^*_{\ell m}(\hat{r}) \frac{\delta T(\hat{r})}{T} \; ; \quad \hat{C}_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

The angular power spectrum measures the amount of variance on various angular scales: $\theta \sim \frac{180^\circ}{\ell}$.

- Just as with the matter power spectrum, different parts of the power spectrum teaches us about different things:



- Sachs-Wolfe region probes the level of density perturbations, with corrections sensitive to things like Ω_{DE} from the integrated Sachs Wolfe (ISW) effect.

- The location of the first acoustic peak serves as a standard ruler. It corresponds to

$$\theta = \frac{v_s t_{rec}}{D_A}$$

← Distance travelled by sound wave in photon-baryon fluid.

← Angular diameter distance to CMB

$$\text{or } \ell \sim \frac{180° D_A}{v_s t_{rec}} \sim 200$$

← higher acoustic peaks are harmonics of this.

This can be used to constrain Ω_K, but there are degeneracies with parameters like Ω_Λ.

⇒ $\boxed{\text{Illustrate with slides}}$

Today we'll start by looking at acoustic peak phenomenology a little bit more closely.

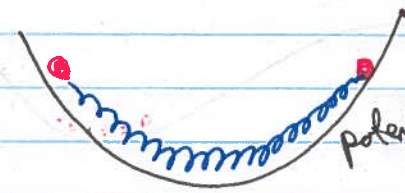
Acoustic Peaks

Let's recall what's going on during this epoch of our Universe's history: scattering between photons and baryons cause them to operate as a coupled photon-baryon fluid prior to recombination.

→ Radiation pressure gives this fluid pressure.
→ The baryons give the fluid extra inertia.

The dark matter creates gravitational potential wells, which try to pull the photon-baryon fluid into them. But since the coupled fluid has pressure, it bounces out.

We can visualize this by imagining two balls connected by a spring, sinking into a potential well



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Of course, we don't just have one potential well in our Universe, but instead, have wells wherever we have overdensities of matter.

In fact, we can do our usual thing of decomposing our overdensity field into different k modes and thinking about how the photon-baryon fluid interacts with each k-mode overdensity.

Show movie with different k modes

Notice how the higher k oscillations seems to oscillate more quickly. This is not surprising, because remember that these are pressure waves / sound waves, so we have a dispersion relation

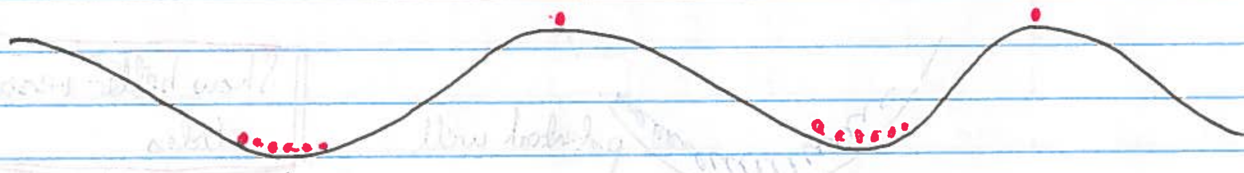
$$\omega = k v_s .$$

$\Rightarrow$ Higher k modes oscillate more quickly (higher ω).

But remember that these oscillations only persist until recombination, because at the point we have decoupling and no more pressure support.

So all the modes get to ~~ex~~ oscillate for time t_{rec}, but since they oscillate at different rates, they get caught in different phases of the oscillation

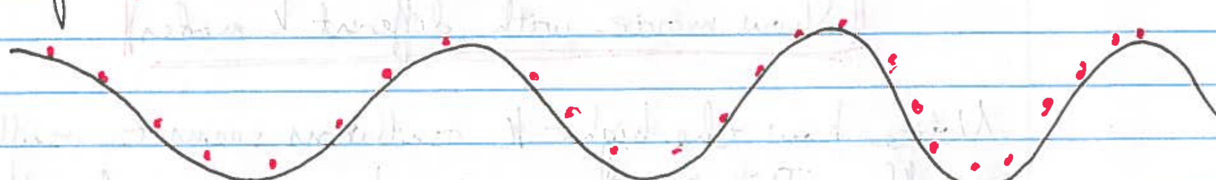
For example, there will be some k mode for which there has just been enough time for the baryons to sink to the bottom:



Maximum compression at bottom of well @ t_{rec}.

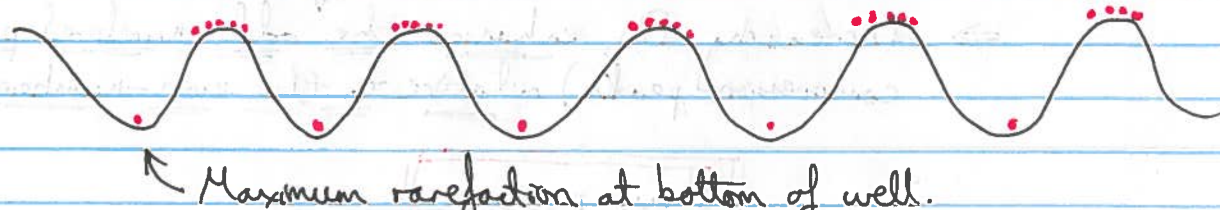
At this particular k-scale — which roughly corresponds to some angular l-scale because the CMB maps inhomogeneities to anisotropies — we can expect ~~a~~ a lot of anisotropy.

At some slightly higher k — and therefore higher l — the baryons might have started to bounce out:



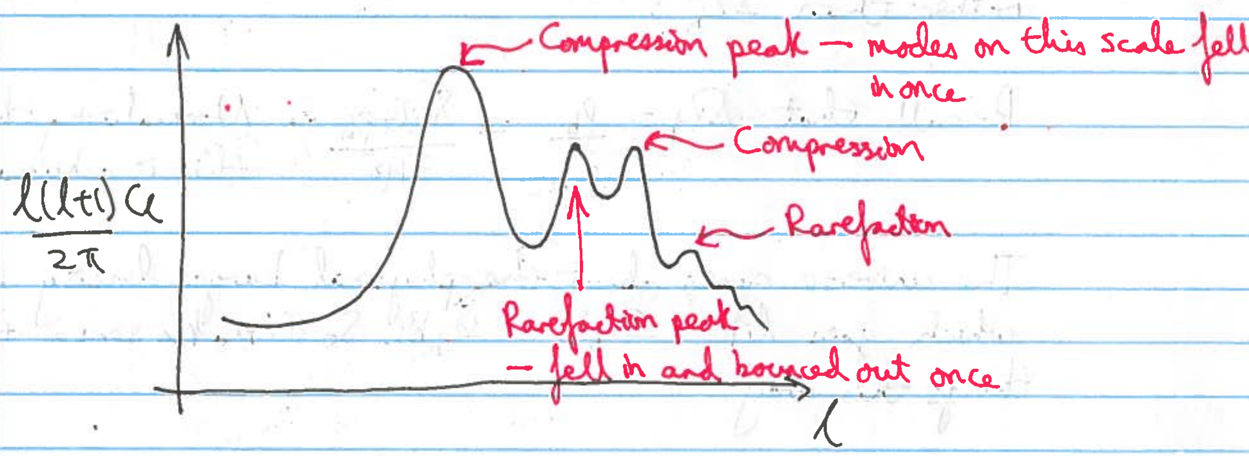
The baryons are fairly evenly spread out, so no strong anisotropies at this scale.

At an even finer scale, the oscillations are even quicker, so you're in a situation where the photon-baryon fluid has had the time to bounce all the way back out the well



The anisotropies are clearly quite strong in this case too.

Each peak in the CMB corresponds to maximum compression / rarefaction



The relative heights of the peaks teach us about some of the detailed physics involved.

For example, suppose I were to turn up Ω_b, ie the amount of baryons in the universe. This increases the inertia of the photon-baryon fluid, making it heavier and causing it to sink lower in the potential wells.

$\boxed{\text{Show pictures}}$

This is called baryon loading, and since it causes baryons to sink lower into potential wells, it enhances the compression peaks.

$\Rightarrow$ Increasing Ω_b enhances the height of the odd-numbered peaks (the compression peaks) relative to the even-numbered peaks.

$\boxed{\text{Show picture}}$

$\Rightarrow$ Ratio of first and second peak tells us about Ω_b.

Incidentally, why do CMB plots often write things like $\Omega_b h^2$ rather than Ω_b?

Recall that $\Omega_b \equiv \frac{\rho_b}{\rho_{crit}} = \frac{8\pi G \rho_b}{3H^2}$. Normalizing things like this is a human convention!

The universe cares about the physical baryon density ρ_b, which goes like $\Omega_b H^2 \sim \Omega_b h^2$. So it makes sense to parametrize things this way.

~~Lets~~ Higher Peaks

What happens to the higher ℓ peaks? We're getting to small scales here, and remember that small scale modes enter the horizon early. Suppose a mode enters during radiation domination.

During radiation domination, gravitational potentials actually decay due to the expansion of the universe!

Comoving Poisson eqn: $k^2 \delta\Phi = 4\pi G \bar{\rho} a^2 \delta$ little growth during radiation domination.

$\bar{\rho} \sim \frac{1}{a^4}$

$\Rightarrow$ $\delta\Phi$ goes down as a increases.

If the potentials decay it is easier for the photon-baryon fluid to climb out, increasing the amplitude of oscillations.

$\Rightarrow$ Show movie

Changing the value of Ω_m changes when our Universe goes from radiation dominated to matter dominated, which therefore changes the magnitude of this effect.

$\Rightarrow$ Show movie

Now, in our Universe the 2nd and the 3rd peaks are about the same height. If one crunches the numbers, this gives an Ω_m that is larger than Ω_b by enough that one is forced to conclude that there is a significant amount of dark matter in our Universe.

$\hookrightarrow$ Note that even though the Ω_m effects can be seen in all the acoustic peaks, we need to measure the first three peaks to be able to disentangle all the other effects.

Damping tail

At even higher ℓ, we see that the power spectrum really dies off. What's happening?

The coupling between photons and baryons is not perfect. As one squashes the photons together, they have some tendency to diffuse out, evening the distribution.

On small scales, the diffusion ~~effect~~ length scale is such that the anisotropies are washed out. $\Rightarrow$ damping tail

This is known as Silk damping.

The damping tail is actually used to constrain the possible existence of new light particles. Recall from our discussion of BBN, during those early times in the universe, relativistic species like photons and neutrinos dominated the energy budget, and therefore – via the Friedman eqn. – determined the expansion rate.

Changing the number particles (eg adding a sterile 4th neutrino) therefore changes the expansion history and the time to recombination. This changes the amount of time the photons have to diffuse, which affects the damping tail in a measureable way!

Other Parameters

The CMB is also sensitive to other parameters!

n_s : Since the CMB is sourced by the primordial matter power spectrum (in a sense), it's sensitive to n_s in $P(k) \propto k^{n_s}$. $\Rightarrow$ Show movie

A_s : This is the amplitude of primordial fluctuations. Higher A_s means higher amplitude CMB power spectrum $\Rightarrow$ Movie

But .... A_s is quite degenerate with τ.

τ : This parameter is due to reionization, when the first galaxies reionized the hydrogen, releasing a bunch of free electrons that could rescatter CMB photons.

\# density of electrons

Path of CMB photons.

Probability of scattering $\sim \tau = \int_{\text{us}}^{\text{CMB}} \sigma_T n_e(z)\, dl$

Thomson cross-section

This is about a 6% effect, so it's not huge (if it were, we wouldn't be able to learn anything from the CMB!) but it's large enough that it needs to be accounted for.

What does it do? ~~Random~~ Scattering jumbles up the hot spots and the cold spots. Since ~~these are random,~~ the CMB is a random field, averaging ~~the~~ pixels together averages down their amplitude.

$\Rightarrow$ Reionization decreases the amplitude of C_l $\boxed{\text{Movie}}$

This means that τ and A_s are degenerate. In fact, for $l \gtrsim 10$, the C_l amplitude is proportional to

$$A_s e^{-2\tau}$$

Squared because it's a power spectrum.

So you can almost perfectly trade off one for another. Fortunately, it turns out that CMB lensing and polarization break this degeneracy somewhat.