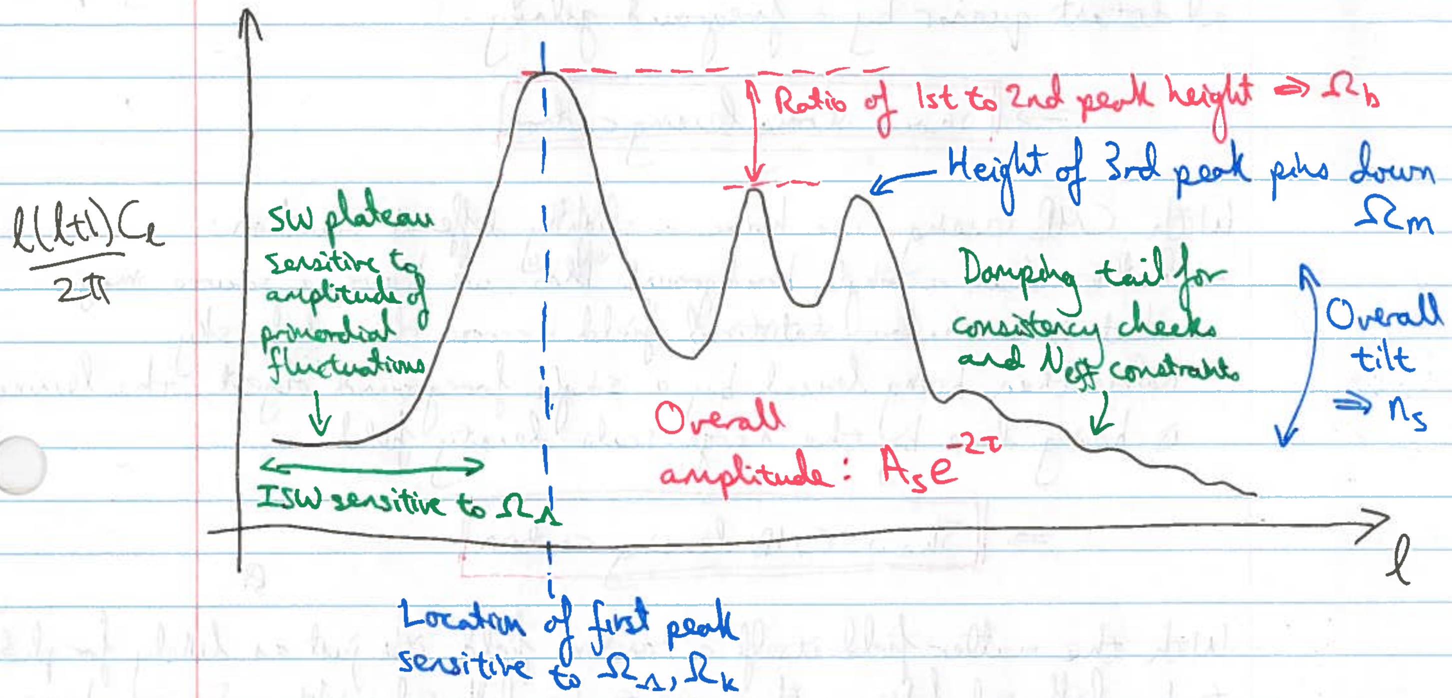
Cosmic Microwave Background Part 3

Believe it or not, we are not yet done mining the information content of the CMB! But let's first recap the information we've already been able to get out of the CMB power spectrum.



It's a shame that the overall amplitude of the power spectrum is given by an expression that is completely degenerate between A_s (amplitude of primordial fluctuations) and the optical depth τ (due to ~~re~~ reionization).

We'll start off today with an effect that can (partially) break this degeneracy.

Gravitational Lensing

Since there are matter fluctuations between us and the surface of last scattering, the CMB photons are affected by gravitational lensing as they travel towards us.

As you know, GR predicts that photons are deflected by gravitational fields. One example of this is the lensing of a distant quasar by a foreground galaxy.

$\Rightarrow$ Show strong lensing cartoon

With CMB lensing, we have a slightly different situation:
- Rather than a single background "blob", we have a source image that is a random statistical field across the whole sky.
- Rather than being lensed by a single foreground object, the lensing is being done by the large-scale density field.

$\Rightarrow$ Show CMB lensing cartoon

With the matter field itself a random field, it's just as likely for photons to be deflected left as they are to be deflected right. So we have to look for the signature of lensing statistically

What does lensing do? Two effects:

(1) Induces non-Gaussianities into the CMB. If we take the unlensed CMB (if we could somehow get at this) and made a histogram of the pixel values, we would get a Gaussian. Lensing induces non-Gaussian signatures. We won't go into the mathematics of this in this class, but what's really cool about this is that it allows one to reconstruct the gravitional potential of the intervening large-scale structure!

$\Rightarrow$ Show Planck reconstruction

careful, though — because the CMB is a single 2D map rather than a 3D map, this is really the projected grav. potential along the line of sight

(2) Peak smearing. One of the effects of lensing is to magnify or demagnify the brightness of ~~images~~ images.

⇒ $\boxed{\text{Show QSO image}}$

With the CMB there is a similar effect, in that some parts of the sky are magnified and other parts are demagnified.

What does this do? Schematically, imagine that

This is not the math that one does for lensing. This is "cartoon math", just to conceptually illustrate.

$$T^{\text{lens}}(\vec{\theta}) = M(\vec{\theta})\, T^{\text{unlensed}}(\vec{\theta})$$

I am using Fourier transform intuition here, but for small patches of the sky, this is a good approx. for spherical harmonic transforms

We are interested in what does this to our power spectrum, so we ~~do~~ Fourier transform/spherical harmonic transform to harmonic space. If I multiply two functions in configuration space, the convolution theorem tells me that the effect is to convolve the functions in harmonic space i.e.

You proved this in your last homework, albeit in a different context!

$$\tilde{T}^{\text{lensed}}(\vec{\ell}) = \int d^2\vec{\ell}'\, \tilde{M}(\vec{\ell} - \vec{\ell}')\, \tilde{T}^{\text{unlensed}}(\vec{\ell}').$$

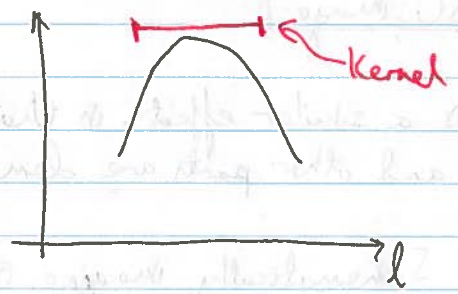
What do convolutions do? They take a function and they "smear it out" using a different function.

⇒ $\boxed{\text{Show convolution movie}}$

What happens with the CMB? In harmonic space, we have a set of hills and valleys — the acoustic peaks. What happens when I convolve over these peaks and valleys with some convolutional kernel (as it's called)?

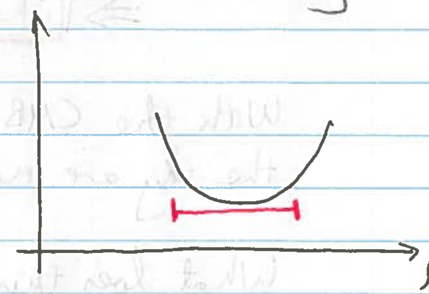
When the Kernel is sliding....

Over a peak



Averaging over ⊢—⊣ mixes the peak with values smaller than it and brings it down.

Over a valley



Averaging over ⊢—⊣ mixes the minimum value with values larger than it, raising it up.

$\Rightarrow$ Lensing reduces the height of the peaks and raises the troughs of the CMB power spectrum.

$\Rightarrow$ $\boxed{\text{Show CMB } C_\ell \text{ as fct. of } A_{lens}}$

Of what use is this? Just as with other gravitationally lensed systems, we can use lensing to study the mass distribution that's doing the lensing. One thing that's very valuable here is that the most dominant lensing signal comes from structures at $z \sim 2$.
$\Rightarrow$ Comparing this to constraints from the primary CMB at $z \sim 1100$, we can test our theories of structure growth!

Alternatively, if the basic picture of fluctuation growth (ie perturbation theory etc.) hangs together, we can get even sharper constraints on parameters.

Eg If we use lensing to estimate the amplitude of fluctuations at low redshifts, we can use perturbation theory to "turn time

Of course this isn't perfect, as there are measurement errors, plus the "rewind" process using perturbation theory itself relies on parameters like Ω_m, which have uncertainties attached to them

"backwards" and predict A_s, partially breaking the $A_s e^{-2\tau}$ degeneracy.

One particularly famous example is what's called the geometric degeneracy.

Recall that we used projection ("geometric") effects to pin down some parameters (Eg Ω_k) by looking at the location (in ℓ) of the acoustic peaks. But multiple effects can shift these peaks, leading to degeneracies, where different parameters could be traded off for one another. Eg traditionally, need galaxy surveys to establish the fact that $\Omega_\Lambda \sim 0.7$. CMB alone was not sufficient.

$\Rightarrow$ $\boxed{\text{Show geometric degeneracy plots}}$

With lensing, the CMB alone tells us that the energy budget of our Universe is dominated by dark energy!

Polarization

Another extraordinarily powerful way to get more information out of the CMB is to measure its polarization.

First, why is the CMB polarized in the first place? Polarization is generated via scattering. In particular, it requires the electrons that are doing the scattering to see a quadrupole of anisotropy around them

$\Rightarrow$ $\boxed{\text{Show movies}}$

Way before recombination, there was lots of scattering. But there was too much! Any net polarization quickly gets averaged to nothing. The polarization that we see in the CMB is due to that last bit of scattering right at recombination and then again at reionization, when there are again free electrons available for scattering.

$\Rightarrow$ Movie time!

Alright, so let's say you make a polarization measurement

$\Rightarrow$ Show WMAP picture + Planck picture

What do you do? The most convenient thing turns out to be to decompose the map into E-modes and B-modes.

We'll discuss why this is important shortly, but for now, they're just a basis.

$\Rightarrow$ Show pictures of pure E and pure B

The unpolarized CMB we've been looking at so far!

This means we can make three maps: T, E, and B

Power spectra, however, are quadratic quantities. This means that from these maps we have several different possible power spectra we can compute:

The "usual" CMB power spectrum

$$C_\ell^{TT},\ C_\ell^{EE},\ C_\ell^{BB},\ \underbrace{\cancel{C_\ell^{EB}},\ \cancel{C_\ell^{TB}}},\ C_\ell^{TE}$$

Don't need to compute these because they are identically zero $\Rightarrow$ the handedness of B means these spectra average to zero.

$\Rightarrow$ Show C_ℓ^{TT}, C_ℓ^{EE}, C_ℓ^{BB}, C_ℓ^{TE} spectra

Several things to note here:

- The polarized power spectra are 10^2 down from the unpolarized power spectrum. ⇒ Polarization maps are 1/10 the amplitude of T.
- The EE power spectrum is out of phase with the TT power spectrum: one peaks at the trough of the other
  ⇒ $\boxed{\text{Show slides}}$
- The oscillations in the TE power spectrum have twice the frequency as the other spectra → Also note that C_ℓ^{TE} can be positive or negative.
  ⇒ $\boxed{\text{Show on slide}}$

How can we explain these facts? Most of the E signals come from density fluctuations, which have the right properties to give the quadrupolar field needed for scattering to produce polarization.

⇒ $\boxed{\text{Show slide picture of a Fourier mode}}$

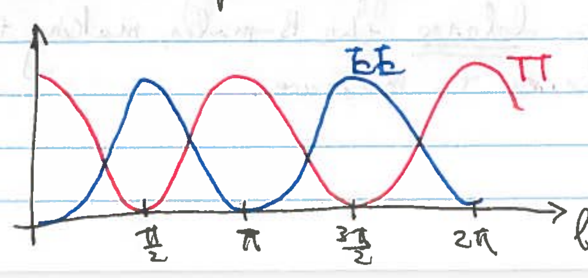
Recall that we need the photons to crash in to scatter off the e^-. This means that the polarization signal is related to the velocity of the fluids.

For the oscillatory behaviour we have here, the temperature / density are out of phase with the velocity. If

These are, again, "cartoon" equations →

$$T \sim \cos(\ell\,\theta_{acoustic}) \quad \text{then} \quad E \sim \sin(\ell\,\theta_{acoustic})$$

If we ~~take~~ now square these:



We get the peaks lined up with the troughs.

And for TE? $\quad TE \sim \sin(\ell \theta_{acoustic}) \cos(\ell \theta_{acoustic})$

$$= \frac{1}{2} \sin(2 \ell \theta_{acoustic})$$

Twice the frequency!

Now what's up with C_ℓ^{BB}? It turns out that the symmetry of B modes is such that density fluctuations cannot create them. Only a tensor fluctuation such as that from a gravitational wave background can generate B modes.

Recall that inflation generates such a background, which is why people are trying to find primordial B modes.

There are some challenges though:

- Nobody knows the amplitude of the signal. If you look back at the notes from inflation, the signal is proportional to the energy scale of inflation — which we don't know.
- Whatever the signal, it is going to be small, and foregrounds (such as polarized dust emission) are a problem.
- Lensing ~~al~~ moves photons around. You can imagine that if I take the E-mode map we saw earlier and randomly jumbled them around, I can get a non-zero B-mode signal.

e lensing modes were t observed e @ McGill!

$\Rightarrow$ $\boxed{\text{Visual on slide}}$

Some people have suggested using our knowledge of large-scale structure to delense the B-modes, making the primordial signal easier / cleaner to measure.

Finally, notice that on large scales there's a bump that's labelled "reionization". Free electrons from reionization can cause scattering, which again sources some polarization power.

This reionization bump goes like $A_s \tau^2$ ← power ⇒ square

↖ prob. scattering

This can help break the $A_s e^{-2\tau}$ degeneracy from C_ℓ^{TT}. However, it's not helped by the fact that τ is on the low end of plausible values, and at these low ℓ one is fighting cosmic variance.

ie the τ we observe