# 39 Astro notes 2018/12/3 - Mon - Cosmology - Cosmic Microwave Background

## 39.1 Cosmic Microwave Background

The cosmic microwave background originates from the first epoch the universe cooled enough to become **transparent to photons**. This occurred when the hydrogen filling the universe became neutral – an event often called "recombination". The physics is related to what sets the surface temperature of cool stars, since both are set by the ionization transition of H.

The temperature at which the CMB was emitted is thus similar to that of the surface of a star, about 3000 K. These photons have been stretched by the expansion of the universe so that we now see the blackbody spectrum as having $T = 2.725 \pm 0.002$ K. The spectrum is very close to a blackbody.

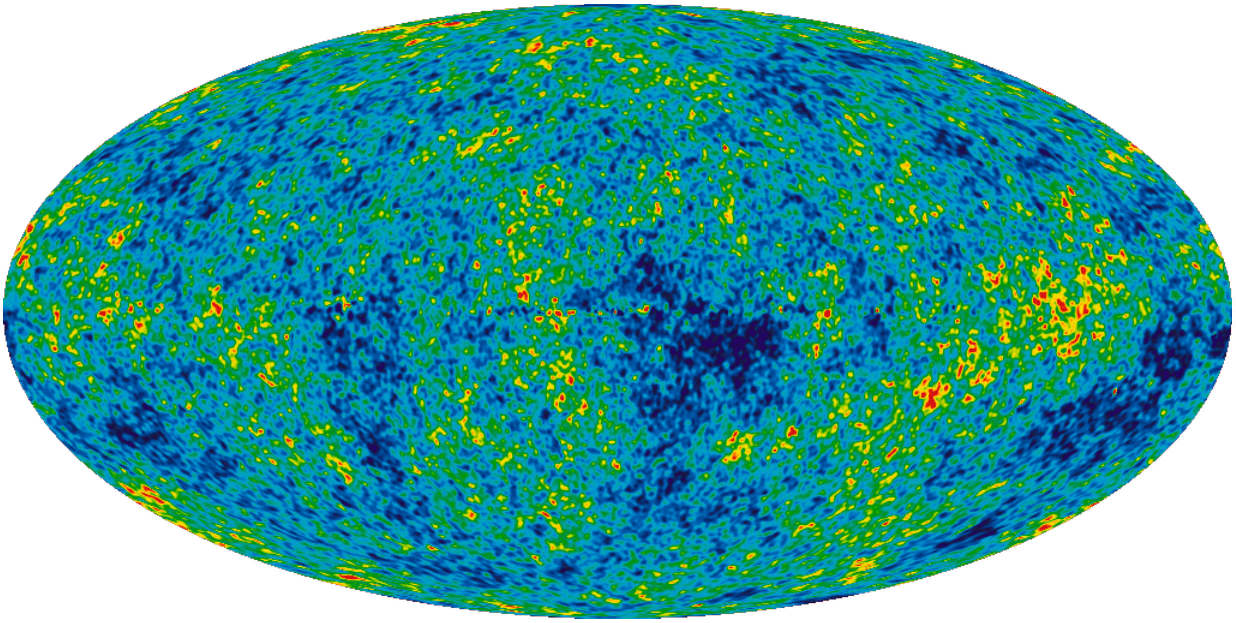
The initial discovery of this effectively proved the "big bang theory". That is the universe has expanded from an earlier hot state into what we see today. The CMB are remnant photons from the first epoch in which the universe became optically thin.

## 39.2 CMB anisotropy

But the anisotropy in the CMB can be used for much more. The large scale structure of the universe (over- and under-densities) are imprinted as small variations in the temperature of the CMB. This can be used to infer properties of universe, specifically its geometry and also the existence of *non-baryonic* dark matter.

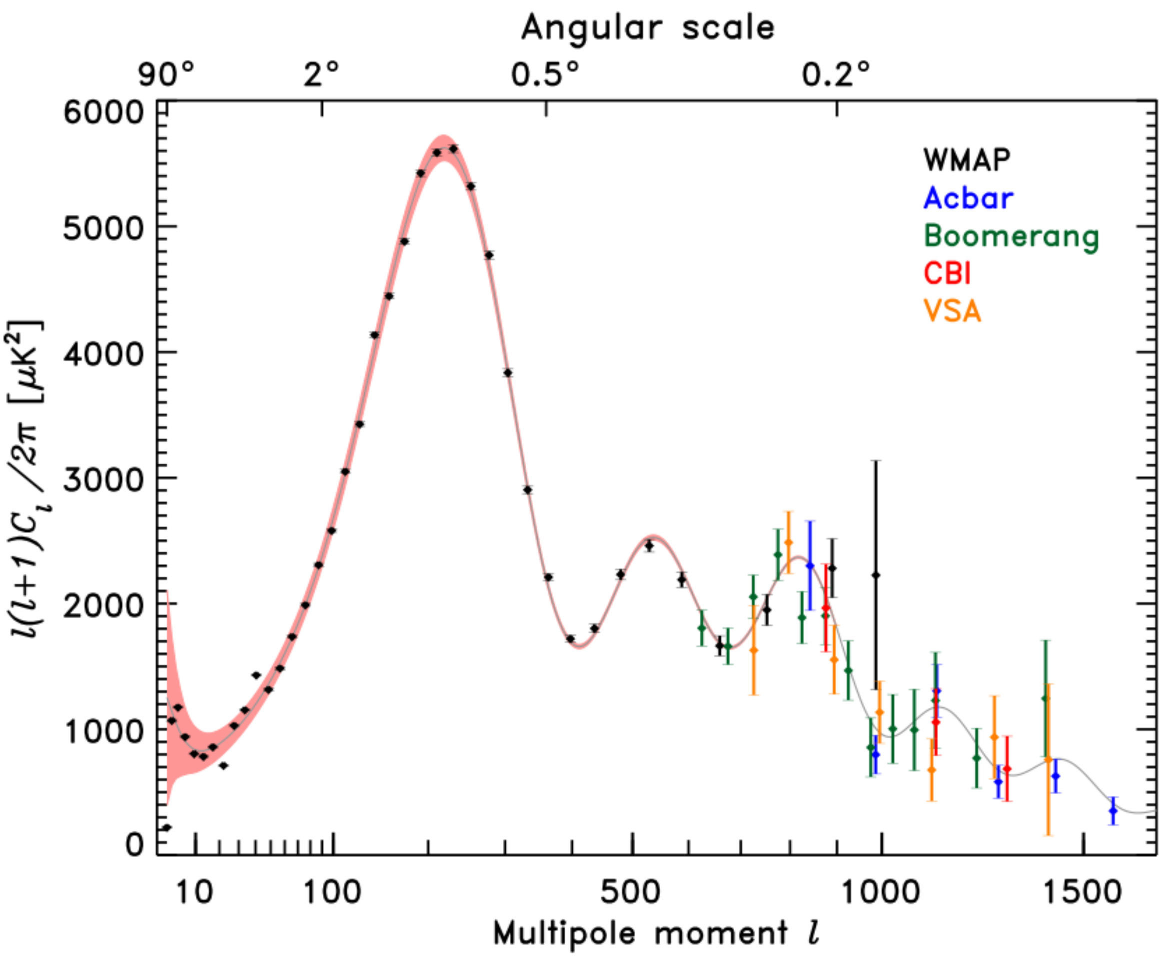
Components want to collapse (fall) but this is resisted by pressure. Each component starts falling at a different time.

On the sky these look like so (amplitude of only $10^{-5}$):



(from http://en.wikipedia.org/wiki/Cosmic_microwave_background )

Acoustic oscillations, driven by random noise, in the early universe had preferred scales due to the different components involved - radiation, neutrinos, dark matter, baryonic matter. In order to study this we take the **angular power spectrum**. This has a peak at about 1 degree angular scale, among other peaks.



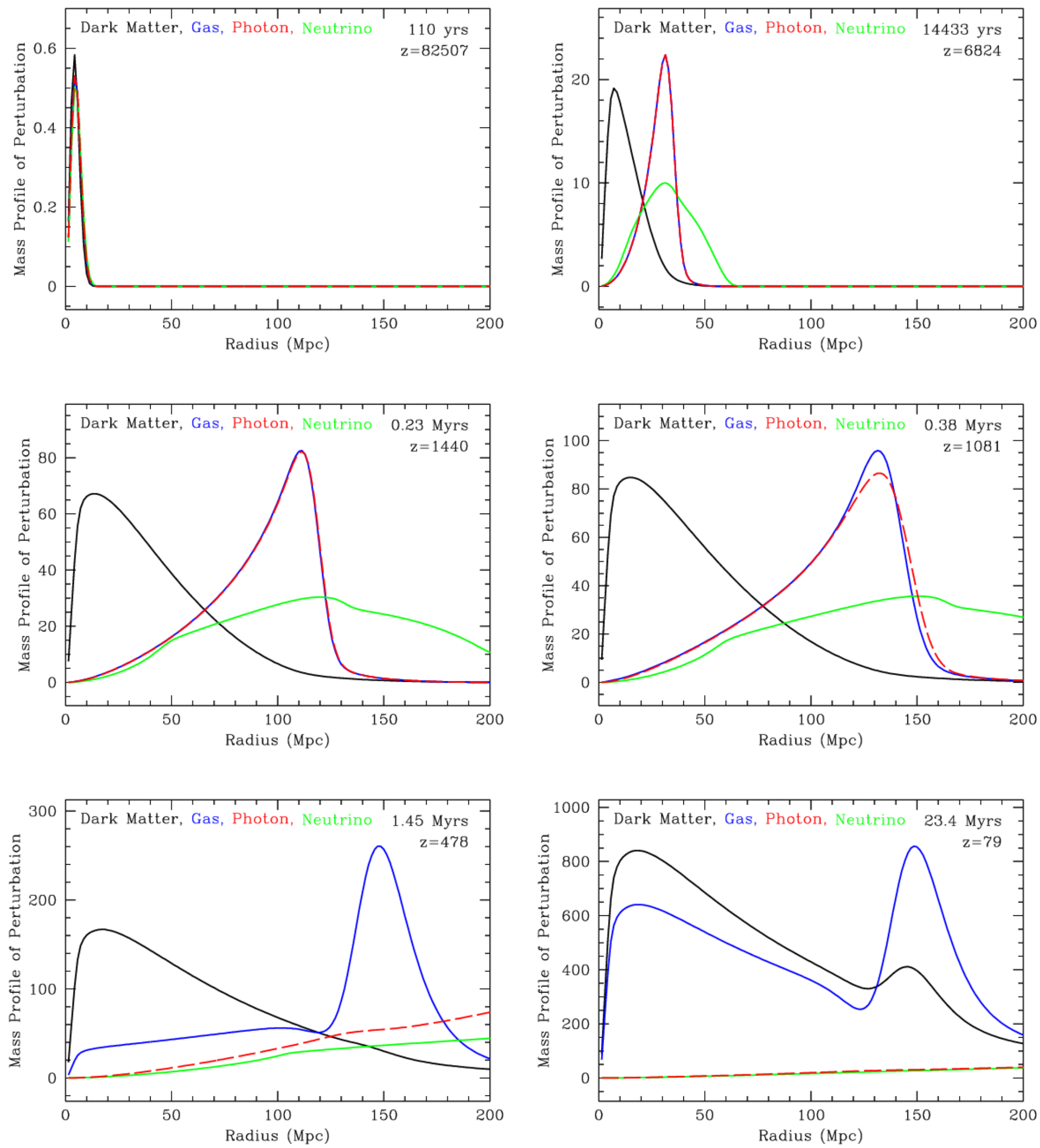

Here the red bands are **Cosmic variance** – the uncertainty because we only have one universe to average over, and this is based on randomness in the early universe. The first peak is the acoustic signature of the baryon-photon coupling - i.e. the preferred scale for inhomogeneities in the universe at the time CMB is emitted. But dark matter has a different (smaller) preferred scale because it had already started to collapse well before the photons started to decouple. So it appears as smaller structure evidenced in the next peak in the power spectrum.

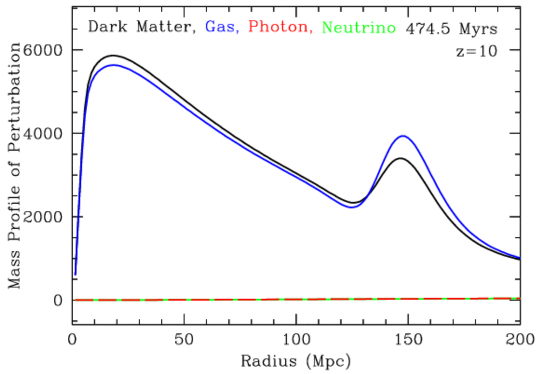
From the structure in the CMB it is possible to conclude that **Dark matter must be electromagnetically neutral** even at high temperatures. Usually this is called non-baryonic, i.e. it can't be anything that contains protons (a baryon, which is therefore charged).

Again, how do we know this? because dark matter decoupled from the hot photons very early in the universe. Photons, due to their high speed, tend to smooth out inhomogeneities. But once a component decouples from photons, its inhomogeneities are no longer smoothed out.

The following sequence of figures demonstrates the decoupling of the differen components for a impulse propagating away from the origin.

(these are from http://www.ias.u-psud.fr/Dark_energy/presentations/castanderBAO_081124.pdf but are very commonly shown when discussing Baryon Acoustic Oscillations. Originally created by Daniel Eisenstein)






In the second pane, can already be seen that the dark matter has decoupled from the "Gas" (Baryons) and photons, which are still coupled. Also neutrinos can also decouple, and begin to stream away.

The CMB IS the analog of the photon component here. It becomes decoupled from the gas just after the third pane ($z \simeq 1000$) and begins to free-stream, leaving the gas behind. The gas begins to then fall back to where most of the mass is, where the dark matter is located. The CMB provides a snapshot of the universe at this time. Thus in the overdensities evident in the CMB we can already see that most of the matter decoupled much earlier, and has already fallen toward overdense regions, and thus must not interact electromagnetically. This has long been a very strong arument for non-baryonic dark matter.

The dark matter also has to be "cold", which means not high velocity due to a large particle mass. Neutrinos are an example of "hot" dark matter.

Toward the end, the dark matter distribution is actually modified by the normal matter, so that there are two preferred scales for structure. This can be found in the distribution of galaxies in space. Since we know the scale from this physics (and the parameters obtained from the CMB) this can be used to construct a standard ruler to measure distances. These are called Baryon Acoustic Oscillations (BAO), and can fulfill a similar role to supernovae - measuring the expansion history of the universe.