The Cosmic Background Radiation (CMB)

Freeze out of CMB photons:

At temperatures $T > 2m_e$ the reaction $\gamma \leftrightarrow e^+ + e^-$ was in thermal equilibrium. I.e. there was as many electron positron pairs created as annihilated. By subsequent expansion the universe was cooling down, i.e. at a certain stage the reaction was not anymore in thermal equilibrium, as no e^+e^- pairs could be created anymore while annihilation could still take place (this can be generalized to basically any particle).

Photons, γ, were, however, still in thermal equilibrium with matter through Compton/Thomson scattering

$$e^- + \gamma \leftrightarrow e^- + \gamma$$

And through reactions with protons (Hydrogen):

$$H + \gamma \leftrightarrow e^- + p$$

With these reactions in equilibrium: photons could not freely propagate!. Once the energy density fell below ionization energy of Hydrogen atoms: electrons not available as scattering partners anymore as they were bound in neutral hydrogen

→ photons could freely propagate through the universe. This is called the freeze out of the photons.

As discussed earlier: two processes leading to freeze out:

a) "Re"combination, i.e. the disappearance of the reaction partners of the photons. After this process the medium became electrically neutral.

→ From freeze out lecture: particle density as function of temperature for non relativistic particles in thermal equilibrium

→ the Saha equation describes the fractional ionization X_e as a function of temperature for processes in thermal equilibrium. It can be shown that "re"combination occurred ($X_e \sim 0.1$) at a redshift z in the range of **1200 to 1300**.

$$\frac{1 - X_e}{X_e} \propto \eta_B \left(\frac{T}{m_e}\right)^{\frac{3}{2}} e^{\frac{B}{T}}$$

Where $\eta_b = \frac{n_b}{n_\gamma}$ is the Baryon to Photon ratio, $m_e$the electron (positron) mass and $B = 13.6\ eV$ the binding energy of the hydrogen atom.

b) Dilution of the reaction partners (Hydrogen, electrons and protons) by Hubble expansion of the universe. For thermal equilibrium to be maintained (validity of Saha equation) we have to demand that the reaction rate $H + \gamma \leftrightarrow e^- + p$ is faster than the Hubble expansion rate. It can be shown that this is the case for redshifts down to $z \sim 1100$. At this time the ionization fraction X_e (Saha equation) is frozen. Also the number of photons per co-moving volume was fixed at this time.

Density of free protons, electrons and positrons determines mean free path of photons. Taking both effects a) and b) into account (recombination and Hubble expansion) it can be calculated that the mean free path for photons is larger than the radius of the observable universe around $z \sim 1050$.

→ Surface of last scattering of cosmic microwave background photons. Since then these photons moved on geodesics and did not participate in any scattering reactions.

Freeze out of photons happened at $T_e \sim 0.25\, eV$, not at temperature $B = 13.6\, eV$ for Hydrogen as one could naively assume as the photon to baryon ratio is $\sim 10^9$, i.e. far from 1. Many photons from the tail of the distribution can still lead to ionization!

Energy spectrum of these photons: black body spectrum.

Temperature measured today is red-shifted to $T_0 = \frac{T_e}{1+z}$.

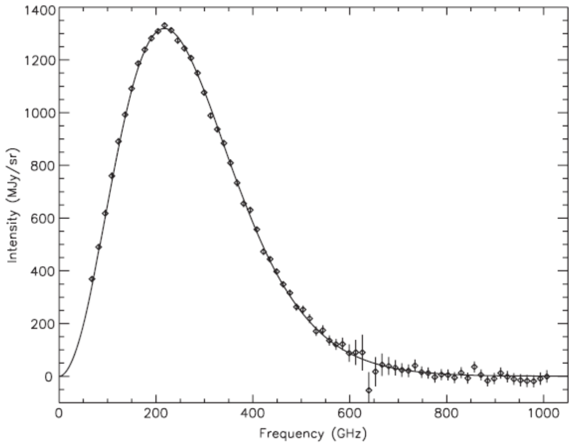
CMB was predicted by G. Gamow in 1946. His main motivation: explain why not all protons ended up in heavy elements (he believed that all isotopes were created in Bing Bang nucleosynthesis).

CMB discovered in 1965 by Penzias and Wilson accidentally: When they tried to measure galactic 21cm line from H_2 with a radio antenna they discovered isotropic noise with temperature $T_{CMB} = (3.5 \pm 1)\, K$, which they first interpreted as the black body radiation from pigeon feces on the antenna.

Nowadays CMB measured to extremely high accuracy. The spectrum fits a perfect black body on the range of three orders of magnitudes! The exact value is given with $T_{CMB} = (2.72548 \pm 0.00057)\, K$ (taken from The Astrophysical Journal, 707:916–920, 2009).

Measurement of $30 - 500\, GHz$ radiation *not trivial*. Many other sources are present: atmosphere, black body radiation of detector, galaxy, etc.

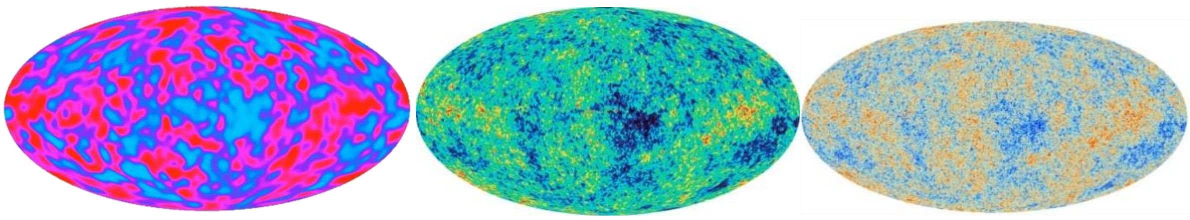
→ Satellite experiments with ultra-cold detectors are necessary to remove most of the background noise.



CMB spectrum measured with the WMAP satellite. The shape fits a perfect black body with temperature $(2.72548 \pm 0.00057)\ K$.

<u>Fluctuations in the CMB:</u>

The fact that we see structures in our universe today implies that there must have been small fluctuations in the early universe from which structures could condense. These fluctuations in the CMB could for the first time be detected with the COBE satellite in 1992 (Nobel prize G. Smoot, 2006). Since then two more satellites have made high precision measurements of the CMB: WMAP (released anisotropy data in 2006) and PLANCK (released data in 2013) with ever finer resolution.



Anisotropies as measured with the COBE (left), WMAP (center) and PLANCK (right) satellites. The different colors display fluctuations of the temperature of the order $\Delta T \sim 0.00001 K$.

The observed temperature fluctuations result from differences in the gravitational potential from which photons at last scattering surface have to escape. This is known as the Sachs-Wolfe Effect:

We know from energy conservation:

$$\underbrace{\left(\frac{\Delta T}{T}\right)_0}_{\text{observed}} = \underbrace{\left(\frac{\Delta T}{T}\right)_e}_{\text{emitted}} + \underbrace{\Phi_e}_{\text{potential}}$$

where the first term on r.h.s. describes intrinsic temperature fluctuation at a given point wrt. average temperature at **surface of last scattering**. The second term describes the gravitational potential at the point of observation. The higher the potential from which photons need to escape, the more energy they lose on the way to observer, the cooler the area will appear (redshift).

But also: the higher the potential, the higher the energy density from which photons have to escape, hence the higher the temperature in these areas.

These are two competing processes → we need a quantitative treatment.

Remember: $a \propto t^{\frac{2}{3(1+\alpha)}}$. One can show that $aT = const$

$$\rightarrow \Delta(aT) = 0 \qquad \rightarrow \frac{\Delta T}{T} = -\frac{\Delta a}{a}$$

$$\rightarrow \frac{\Delta a}{a} = \frac{2}{3(1+\alpha)} \frac{\delta t}{t}$$

From general relativity we know (time dilation):

$$\frac{\delta t}{t} \approx \Phi.$$

Combining the expressions yields:

$$\left(\frac{\Delta T}{T}\right)_e = -\frac{\Delta a}{a} = -\frac{2}{3(1+\alpha)} \frac{\delta t}{t} = -\frac{2}{3(1+\alpha)} \Phi_e$$

or

$$\left(\frac{\Delta T}{T}\right)_0 \cong \frac{1+3\alpha}{3+3\alpha} \Phi_e$$

Hence, for a matter dominated universe with $\alpha = 0$ we can write

$$\left(\frac{\Delta T}{T}\right)_0 \cong \frac{1}{3} \Phi_e$$

This means that energy loss due to escape from gravitational potential is bigger than additional energy due to higher temperature in denser areas.

→ CMB allows us to measure the gravitational potential at time of "re"combination/photon decoupling. The fluctuations are visible over regions that are far bigger than the event horizon at decoupling. This means that the fluctuations are intrinsic!

Another effect occurs when CMB photons during their journey from emission to observation are travelling through gravitational potentials of the large scale structure. When falling into the potential they gain energy, while they lose energy again, when climbing out of the potential. During their propagation through the potential, however, the universe is expanding. This expansion causes a distortion of the potential and effectively a reduction of the potential depth. Hence, in effect the CMB photons use less energy to leave the potential well. This Integrated Sachs Wolfe (ISW) effect is observable in the CMB power spectrum.

The CMB is polarized by Thomson scattering of photons off electrons during decoupling. The polarization pattern induced by gravitational wells has no curl and is called E-mode polarization. Another mechanism to induce polarization is due to gravitational waves emitted in the early universe (inflation). This component of the polarization pattern is predicted to have a curl, and is called B-mode polarization. There is no other known mechanism that could produce B-mode polarization. Observation of B-mode polarization would, hence, be direct evidence for gravitational waves produced during inflation.

To quantify the CMB fluctuations as a function of angular separation on the sky, expansion in spherical harmonics is used:

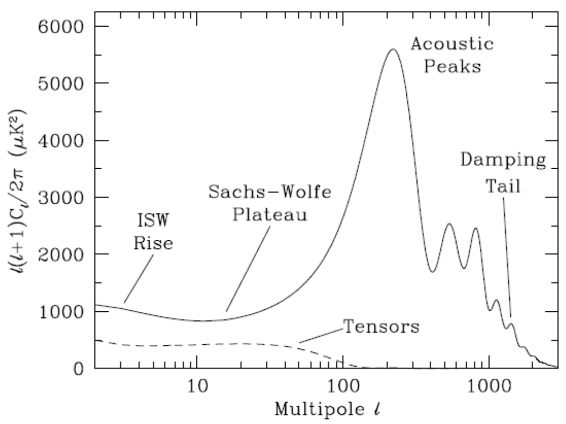
$$\frac{\Delta T(\vec{n})}{T} = \sum_{l=2}^{\infty} \sum_{m=-l}^{m=l} a_{lm} Y_{lm}(\theta, \varphi)$$

The dipole term $l = 1$ is omitted as it is governed by the peculiar velocity of earth in the coordinate system of co-moving coordinates.

From precise measurement of the temperature map, all a_{lm} can be determined and an average can be given by

$$C_l = \langle a_{lm} a_{lm}^{*} \rangle = \frac{l}{2l+2} \sum_{m=-l}^{l} a_{lm} a_{lm}^{*}$$

C_l contains the information on the average temperature fluctuation at an angle corresponding to multipole l.



Theoretical prediction for CMB fluctuations for a ΛCDM model. The contribution expected from gravitational waves is also shown (Tensors).

The precise form of the power spectrum of the CMB fluctuations is closely linked to the content and geometry of the universe at time of decoupling. This can be understood by considering the content that is in thermodynamic equilibrium as a fluid in a given geometry. Oscillations inside the universe will appear, as photons and other particles fall into gravitational potential and will be stopped and eventually even reversed by radiation pressure inside the dense regions. This means that the baryon photon fluid starts to perform "acoustic oscillations".

The frequency and amplitude of these oscillations depends on the exact configuration. The angle and amplitude of the first mode of oscillations is determined by the Hubble radius and the geometry of the universe at time of decoupling, hence is sensitive to the cosmological parameter $\Omega_{tot} = \Omega_m + \Omega_\Lambda - \frac{k}{aH} = \Omega_m + \Omega_\Lambda + \Omega_k$.

It is the baryon photon fluid that is oscillating in the gravitational potential. Latter has a contribution from dark matter that is not in thermal equilibrium with the baryon-photon fluid. Therefor the power spectrum is also sensitive to Ω_{DM} and Ω_B.

The baryon to photon ratio η_b determines the amplitude of the first mode peak. The ratio of Ω_B and Ω_{DM} determines the relative heights of first and second peak. Many other cosmological parameters can be determined from the acoustic peaks of the CMB anisotropy.

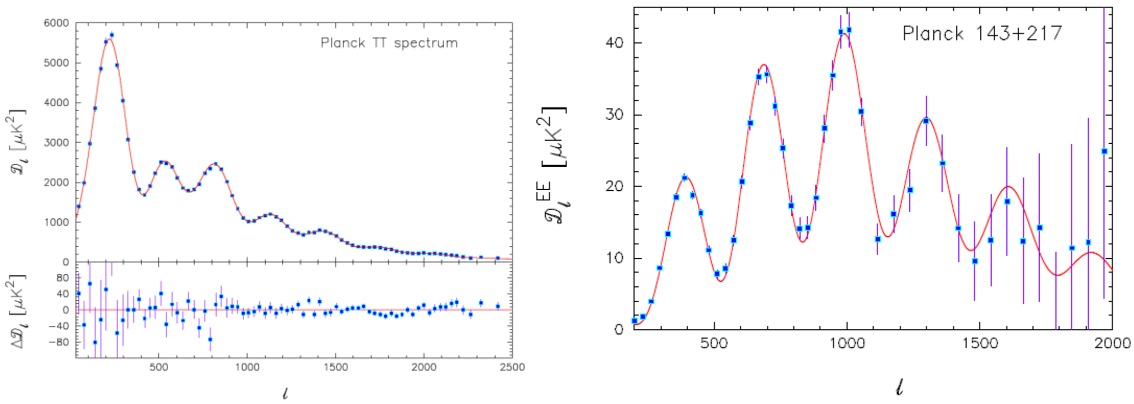
Oscillations in the CMB at small scales are suppressed, as the photons escape from a finite shell thickness: Variations corresponding to the thickness of the shell are washed out: Silk damping.

The ESA PLANCK satellite was launched in 2008. The PLANCK collaboration has released their data in 2013. Cosmological parameters could be determined with unprecedented precision.

With the PLANCK satellite also fluctuations in the polarization of the CMB could be measured for the first time.

Ω_{tot}	$1.0010^{+0.0033}_{-0.0031}$	
$\Omega_m h^2$	0.1423±0.0029	Ω_m= $0.315^{+0.016}_{-0.017}$
Ω_Λ	0.685±0.016	
$\Omega_B h^2$	0.02207±0.00027	Ω_B = 0.0485±0.0012
$\Omega_{DM} h^2$	0.1196±0.0031	Ω_{DM} = 0.2633±0.0095
η_b	$(6.047\pm0.074)\cdot10^{-10}$	
Age of the universe	$(13.813\pm0.058)\cdot10^{9}yr$	
H_0	$(67.3\pm1.2) km \cdot s^{-1} \cdot Mpc^{-1}$	
z_* at decoupling	1090.37±0.65	

Set of parameters as derived from the PLANCK CMB anisotropies assuming a ΛCDM cosmology.



Power spectrum of temperature fluctuations of the CMB as measured with the PLANCK satellite compared to the best fit ΛCDM model (left). With PLANCK also the anisotropies in polarization of the CMB could be measured with high precision (right). The red line represents the prediction of the CMB polarization as computed from the best fit ΛCDM model (taken from A&A 571, A16, 2014)*.*

Oscillations of the baryon-photon fluid in the early universe should also lead to a characteristic density fluctuation of galaxies in the observable universe (known as Baryon Acoustic oscillations, BAO). These fluctuations could be found in large scale galaxy surveys like SDSS (Sloan Digital Sky Survey).