Cosmology II: The thermal history of the Universe

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1. The thermal history of the Universe
2. The cosmic microwave background
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Thermal history

In the past the Universe was not only much denser than today but also much hotter.

The most remarkable events of the hot Universe:

- Recombination (electrons and protons combine to neutral hydrogen).

Age of the Universe: $t_0 \sim 13.7$ billion years
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- Inflation?

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- At \( T \approx 3000\text{K} (t \approx 300'000\text{years}) \) the Universe is 'cold' enough that protons and electrons can combine to neutral hydrogen.

- After this, photons no longer scatter with matter but propagate freely. Their energy (and hence the temperature) is redshifted to \( T_0 = 2.728\text{K} \) today, corresponding to a density of about 400 photons per \( \text{cm}^3 \).
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- It represents a 'photo' of the Universe when it was about 300’000 years old, corresponding to a redshift of $z \simeq 1100$. 
The cosmic microwave background: the spectrum

(Fixen et al. 1996) Nobel Prize 1978 for Penzias and Wilson, Nobel Prize 2006 for Mather

\[ T_0 = 2.728 \text{K} \approx -270.5^\circ \text{C} \]
The cosmic microwave background: anisotropies

Smoot et al. (1999), Nobel Prize 2006

Map of the CMB temperature: perfectly isotropic.

Subtracting the monopole a dipole of amplitude $\sim 10^{-3}$ becomes visible. It is mainly due to the motion of the solar system with respect of the sphere of emission (last scattering surface).

And what is this? Left over after subtracting the dipole. Fluctuations of amplitude $\sim 10^{-5}$. 

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ESA/Planck (2013)
The cosmic microwave background: anisotropies

**Angular scale**

\[ D_\ell [\mu K^2] \]

**Multipole moment, \( \ell \)**

ESA/Planck (2013)

\( \ell = 200 \) corresponds to about \( 1^\circ \). ⇒ ’acoustic’ peaks. \( (\theta \approx 180^\circ / \ell) \)

(This is roughly the double of the angular size of the full moon (or of the sun).)
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- The second peak corresponds to fluctuations which have had time to make exactly 1 contraction and 1 expansion since horizon entry until decoupling (under density).
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- The second peak corresponds to fluctuations which have had time to make exactly 1 contraction and 1 expansion since horizon entry until decoupling (under density).
- The third peak corresponds to fluctuations which have had time to make exactly 2 contractions (and 1 expansion) since horizon entry until decoupling.
Combined CMB data

![Graph showing combined CMB data from various experiments including Planck, WMAP9, ACT, and SPT. The graph plots the angular power spectrum \( D_\ell [\mu K^2] \) against \( \ell \), ranging from \( \ell = 2 \) to \( \ell = 3000 \). The data points for each experiment are indicated with different colors and error bars.

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The cosmic microwave background: anisotropies

The patches which have of peak amplitude temperature fluctuations are standard rulers. Their size is given by the age of the Universe at the time of decoupling (recombination). The angle under which we see these patches determines the distance to the surface of last scattering. \( z = z_{\text{dec}} \approx 1100 \), \( d = r/\theta \).

The amplitude of the peaks depends on the matter density
\[
\rho_m \propto \Omega_m H_0^2 = (13 \pm 2) \times 100(\text{km/s/Mpc})^2
\]
and the difference of the amplitude of even and odd peaks depends strongly on the density of electrons and hence baryons,
\[
\rho_b \propto \Omega_b H_0^2 = 2.2 \pm 0.3 \times 100(\text{km/s/Mpc})^2 \ll \Omega_m H_0^2.
\]

Most of the matter in the Universe is dark and non-baryonic!
Baryon acoustic oscillations

The acoustic peaks are also visible in the matter power spectrum. (= The mean square amplitude of fluctuations of a given size.)

![Graph showing the matter power spectrum before and after reconstruction](image)

from Anderson et al. '12

SDSS-III (BOSS) power spectrum.
The cosmological composition

Data: CMB + BAO + SN Ia

\[ H_0 = 67.8 \pm 1 \text{km/s/Mpc} \]
\[ = h_{100} \text{km/s/Mpc} \]
\[ \Omega_m = 0.31 \pm 0.01 \]
\[ \Omega_b h^2 = 0.0221 \pm 0.0002 \]
\[ \Omega_K = -0.0005^{+0.0065}_{-0.0066} \]
\[ \Omega_\Lambda = 0.69 \pm 0.01 \]
\[ \Omega_{\text{rad}} h^2 = 0.48 \times 10^{-5} \]
\[ \text{age} = 13.80 \pm 0.04 \text{Gyr} \]
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Dark matter

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The first to postulate dark matter was the Swiss astronomer Fritz Zwicky. He realized that binding galaxy clusters gravitationally, requires about 100 times more mass than the mass of all its stars (HPA, 1933).

In the 70ties, the American astronomer Vera Rubin has shown that also galaxies are dominated by dark matter which contributes about 10 times more to their mass than the stars.
Dark matter

Rubin found that the rotation curves of test particles (stars, hydrogen atoms) rotating around galaxies do not show the expected decay of the velocity,

\[ v^2 = \frac{GM}{r}, \quad v \propto \frac{1}{\sqrt{r}} \]

but have \( v = \text{constant} \). Kepler’s law then requires that \( M \propto r \).
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- CMB anisotropies (and nucleosynthesis) require $\Omega_b h^2 \approx 0.02$
- Hence most of dark matter (env. 85%) is non-baryonic.
What could this dark matter be?

- A stable particle which do not couple to photons.
- Neutrino (cannot be bound in dwarf galaxies, too little small scale structure).
- Sterile Neutrino which is more massive but less abundant?
- Neutralino (stable particle in most simple models of super-symmetry (LHC)?)
- Axion (Hypothetical stable particle required to solve the 'strong CP problem')
- Primordial black holes?
- Wimpzillas?
- Gravitinos?

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Dark energy models

- Cosmological constant / vacuum energy
  Provides a good fit to the data, but nobody understands its value and which it comes to dominate exactly ’now’.

![Graph showing the evolution of energy density with log(1+z)](image-url)
Dark energy models

- **Quintessence**
  A scalar field which first follows the scaling of matter and radiation and has started to dominate recently.
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\[ w = \frac{P}{\rho_E} \]

=pressure/(energy density)
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Dark energy models

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- **Backreaction**: If structure formation leads to relevant modifications of the geometry, this could modify the relation between distance and redshift...
Conclusions

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- **Baryons**
  Only about 5% of the energy density of the present Universe is in the form of matter as we find it in our solar system, ordinary atoms made out of baryons and electrons.