Die thermische Geschichte des Universums

1) $T \approx 8 \times 10^9$ K - **neutrino freeze out**

   a) Elementary particles are at equilibrium when

   b) Cosmic expansion reduces the energy density and therefore also the temperature of the universe. reactions however are energy (and therefore temperature) dependent so an expanding universe will influence what reactions occur

   c) The neutrino freeze out mean, that reactions involving neutrinos become rare and therefore the existing neutrinos decouple from the evolution of the rest of the universe

   d) No one has measured the neutrino background, as its energy is really low and neutrinos are hard to detect.

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2) $T \approx 8 \times 10^8$ K - **Primoridial nucleosynthesis**

   a)

$$\frac{n_\mathrm{n}}{n_\mathrm{p}} = \mathrm{e}^{-\frac{\Delta mc^2}{k_\mathrm{B}T}} = \underline{\underline{0.15}}$$

   b)

$$\left.\frac{n_\mathrm{n}}{n_\mathrm{p}}\right|_{t=3\ \mathrm{min}} = \mathrm{e}^{-\frac{t}{\tau}} \left.\frac{n_\mathrm{n}}{n_\mathrm{p}}\right|_{t=0} = \underline{\underline{0.125}}$$

   c)

$$Y = \frac{4n_\mathrm{He}}{4n_\mathrm{He} + n_\mathrm{H}} = \frac{2n_\mathrm{n}}{n_\mathrm{p} + n_\mathrm{n}} = \frac{2(n_\mathrm{n}/n_\mathrm{p})}{1 + (n_\mathrm{n}/n_\mathrm{p})} = \begin{cases} 0.265 & t = 0 \\ 0.222 & t = 3\ \mathrm{min} \end{cases}$$

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3) $T \approx 3000$ K - **recombination**

   a) 13.6 eV $\approx$ 158000 K, which is higher than 3000 K. The reason for this is, that at this time most of the hydrogen wasn't at ground state but at a and therefore the energy needed to ionise it is much less.

   b) once protons were able to from neutral hydrogen, photons stopped being absorbed and emittet continously, and therefore the existing photons were able to persist and travel much greater distances than before. The CMB is therefore a snapshot of the universe at the moment neutral hydrogen formed and the universe became transparent

4) $T \approx 50$ K - **reionization**
   a) Today the universe is mostly ionized. This was caused by atoms forming gas clouds and and heating up, ionizing
   b) Information about the reinization era can be extracted from the CMB and from quasar spectra