Lecture 15

$\Omega_M \approx 0.3$

$\Omega_B = \Omega_{stars} + \Omega_{gas, dust, ..} \sim 0.05$ (from cosmic microwaves, and big bang nucleosynthesis, see later)

$\Omega_M - \Omega_B \equiv \Omega_{DM}$ Dark matter!

[Invisible matter would be a better name - has to be electrically neutral, otherwise would shine]

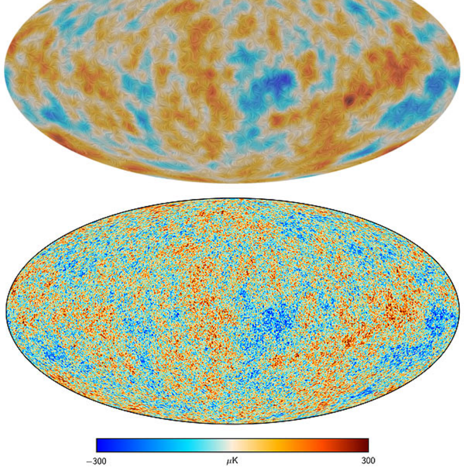
$$\boxed{\Omega_{DM} \sim 0.25}$$

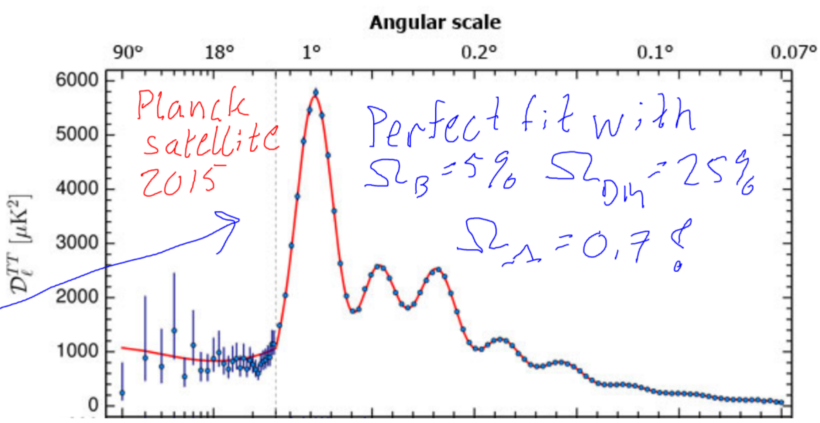
But what is it? Standard Model of particle physics has no good candidate (neutral, stable, ..)

$\Rightarrow$ non-baryonic matter

Indications for the existence of dark matter:

- CMB $\Omega_{DM} \sim 25\%$
- Rotation curves of galaxies
- Gravitational lensing
- Big bang nucleosynthesis $\Rightarrow \Omega_B \approx 5\%$





Planck satellite 2015

Perfect fit with $\Omega_B = 5\%$ $\Omega_{DM} = 25\%$ $\Omega_\Lambda = 0.7$!

Angular correlations of temperature

The early universe and the Cosmic Microwave Background

(CMB)

Friedmann: $$\frac{H^2}{H_0^2} = \Big[\underbrace{\Omega_M(1+z)^3}_{\equiv\,\Omega_m(z)} + \underbrace{\Omega_R(1+z)^4}_{\Omega_r(z)} + \underbrace{\Omega_K(1+z)^2}_{\Omega_k(z)} + \underbrace{\Omega_\Lambda}_{\Omega_\Lambda}\Big]$$

$t = t_0 \Rightarrow z = 0$; $\Omega_M = 0.3$, $\Omega_R \sim 10^{-5}$, $\Omega_K < 10^{-3}$, $\Omega_\Lambda = 0.7$

at $z = 10^4$ $$\frac{\Omega_r(z)}{\Omega_m(z)} \sim \underbrace{\frac{\Omega_R}{\Omega_M}}_{\approx 10^{-4}}(1+10^4) \approx \underline{1}$$

This was the epoch of <u>matter-radiation equality</u>

For earlier times (larger z), radiation dominated

CMB gives perfect Planck curve (COBE satellite measurements)

$\Rightarrow \rho_r = \alpha_{rad} \cdot T^4 \sim T^4$ (see formula sheet for α_{rad})

But we also had $\rho_r \sim \left(\frac{a_0}{a}\right)^4 = (1+z)^4$

$\Rightarrow$ temperature $T = T_0(1+z)$ $\quad T_0 = 2.73\,K$

At $z = 10^4$: $T = T_0(1+10^4) \approx 27000\,K$

Very hot, ionized <u>plasma</u> $\Rightarrow$ rapid scattering of photons

As the universe expanded, it became cooler, and at $z \sim 1100$ $[T \sim 3000\,K]$ it became transparent to photons ("the surface of last scattering")

This light can still be seen, but due to redshift it is now at a temperature of $T_{CMB} = \frac{3000K}{1100} = 2.7\,K$

visible light $\longrightarrow$ microwaves, due to expansion!

At $t = t_0$, $T_{CMB} = 2.7K$ $\langle E_\gamma \rangle = 3k_B \cdot T_{CMB} \approx 7 \cdot 10^{-4}\,eV$

Number density now, $n_\gamma^0 = \frac{\rho_r(t_0)}{\langle E_\gamma \rangle} \sim 360\ \text{cm}^{-3}$

[$\rho_r(t_0) = \alpha_{rad} T^4 = 7.565 \cdot 10^{-16}\ \text{J}\,\text{m}^{-3}\text{K}^{-4} \cdot (2.73\text{K})^4 = \ldots \frac{1}{1.602 \cdot 10^{-19}}\ \text{eV} = 0.26\,\text{eV/cm}^3$]
see α_{rad} in formula sheet

we had $\Omega_{Baryon} \sim 0.05$; $\rho_c^0 \approx 0.5 \cdot 10^{-5}\ \text{GeV/cm}^3$
[see formula sheet; $h \sim 0.7$]

$\Rightarrow \rho_B \approx 0.05 \cdot \rho_c^0$ assume all is hydrogen

$$\Rightarrow n_B = \frac{\rho_B}{m_H} \simeq \frac{0.05 \cdot 0.5 \cdot 10^{-5}\ \text{GeV}\,\text{cm}^{-3}}{1\ \text{GeV}} \sim 3 \cdot 10^{-7}\ \text{cm}^{-3}$$

$$\Rightarrow \frac{n_B}{n_\gamma} \approx \frac{3 \cdot 10^{-7}\ \text{cm}^{-3}}{360\ \text{cm}^{-3}} \sim 10^{9}$$

$\because$ 1 billion photons per nucleon!

[Side remark: Where did all the photons come from?
We don't know, but it probably was related to the mechanism that removed all antimatter in the universe:

10^9 antiparticles + (10^9+1) particles $\rightarrow$ 1 particle + 10^9 photons]

The 10^{-9} difference in numbers between particles and antiparticles is a violation of C and P, "CP violation".

How did the plasma become electrically neutral, and therefore transparent?

Processes at $z \sim 10^4$:

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

$$\text{H} + \gamma \leftrightarrow p + e^-$$

neutral gas

At $z \sim 1100$, mostly in $\leftarrow$ direction, since temp. too low (~ 0.25 eV) to ionize hydrogen
leftward

From $z \sim 10^3$ (at $t \sim t_{decoupling}$) until recently, the universe was matter dominated. (Equality at $z \sim 10^4$)

Matter domination

$\Rightarrow \quad a(t) \sim t^{2/3}$ (see lecture 13)

Now, $t_0 \approx 4 \cdot 10^{17} s$ (13 billion years)

Estimate of t_{dec}:

$$T(t) = \frac{T_0}{a(t)} \left(= T_0 \cdot (1+z) \right)$$

$$\Rightarrow a(t) = \frac{T_0}{T(t)} = \left(\frac{t}{t_0} \right)^{2/3} \Rightarrow \frac{t_{dec}}{t_0} = \left(\frac{T_0}{T_{dec}} \right)^{\frac{3}{2}} = \left(\frac{2.7}{3000} \right)^{3/2}$$

$$\Rightarrow t_{dec} = t_0 \cdot \left(\frac{2.7}{3000} \right)^{3/2} = 1.1 \cdot 10^{13} s = 340000 \text{ yrs}$$

—— x ——

The earliest universe ($z > 10^4$) was very simple:

$$H^2 = \left(\frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \rho_\gamma = \frac{8\pi G}{3} \alpha_{rad} T^4$$

Radiation domination $\Rightarrow a(t) \sim \sqrt{t}$ (see lect. 13)

$$\Rightarrow H = \frac{\dot{a}}{a} = \frac{1}{2t}$$

Thus $\left(\frac{1}{2t} \right)^2 = \frac{8\pi G_N}{3} \alpha_{rad} T^4 \Rightarrow \ldots \Rightarrow$

$$\Rightarrow \boxed{T(\text{MeV}) \approx \frac{1}{\sqrt{t(\text{sec})}}}$$ During radiation domination

Thus, 1 sec after the big bang, the temperature corresponded to 1 MeV (i.e. $k_B \cdot T \sim 1$ MeV)

$k_B \sim 8.62 \cdot 10^{-5}$ eV/K $\Rightarrow T = 1$ MeV $\leftrightarrow 10^{10}$ K

"Hot big bang"

$k_B T = 1 - 10$ MeV typical binding energy of nuclei

When $k_B T$ was $\gg 10$ MeV all processes were in (near) thermal equilibrium; when temperature was 1-10 MeV the distribution was near Maxwell-Boltzmann

$$n \sim (mc^2)^{3/2} e^{-\frac{mc^2}{k_B \cdot T}} \quad (mc^2 \gg E_{kin} \text{ at } 1-10 \text{ MeV})$$

$$\Rightarrow R_n \equiv \frac{n_n}{n_p} = \left(\frac{m_n}{m_p}\right)^{3/2} e^{-\frac{\overbrace{(m_n - m_p)}^{\equiv \Delta m} c^2}{k_B \cdot T}}$$

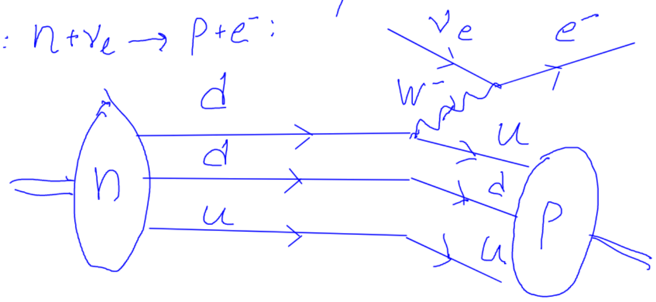
$\Delta m c^2 \approx 1{,}3$ MeV (see nuclear physics part)

$\Rightarrow R_n \approx 1$ for $k_B T \gg 1{,}3$ MeV

How can a neutron convert to a proton and vice versa?

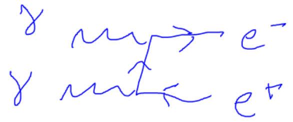
Answer: Only weak interactions can do that!

Ex: $n + \nu_e \to p + e^-$:



$$n + \nu_e \leftrightarrow p + e^-$$
$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

(positrons are plentiful due to $\gamma + \gamma \leftrightarrow e^+ + e^-$ etc.



)

As temperature decreased to $\sim \Delta m = 1{,}3$ MeV processes go faster to the right (as protons are lighter)

More exact calculation $\Rightarrow$ $k_B T \sim 0{,}8$ MeV when neutrons "freeze-out" (are not generated thermally)

$$\Rightarrow \frac{n_n}{n_p} \sim e^{-\frac{1{,}3 \text{ MeV}}{0{,}8 \text{ MeV}}} \approx \frac{1}{5} = 0{,}2 \quad \text{at } t \sim 1\text{s}$$

But neutrons can decay $n \to p + e^- + \bar{\nu}_e$ $\quad \tau_n \sim 880$ s

($\tau_{1/2} \sim 610$ s)

Neutrons continue decaying, until they are "safe" inside stable nulei

deuterium

$$p+n \leftrightarrow D+\gamma\ ,\quad D+p \leftrightarrow {}^3He+\gamma$$
$$D+D \leftrightarrow {}^3He+n \quad (\text{or } {}^3H+p)$$
$$D+{}^3He \leftrightarrow {}^4He+p\ ,\quad D+{}^3H \leftrightarrow {}^4He+n$$

When $t \sim 300s$, all deuterons had become ^3He or $\underbrace{^4He}_{\text{dominant}}$

How many neutrons were there remaining?

$$\frac{n_n}{n_p} = \frac{1}{5}\, e^{-\frac{300s}{880s}} \sim \frac{1}{7}$$

t/τ_n

~ all end up in helium, ^4He

So, for 2 neutrons there were 14 protons (ratio was 1:7), 2n+2p give one helium nucleus ⇒ 12 protons remaining. So for every 2+14=16 nucleons, 1 helium nucleus and 12 protons (hydrogen) are formed.

⇒ mass ratio (each ^4He has 4 nucleons):

$$Y_{^4He} = \frac{4}{16} \simeq 0.25$$

(More exact calculation ⇒ $Y_{^4He} \simeq 0.24$)

The rest is protons (i.e. hydrogen) plus very small amounts of Li, Be, D, ^3He (no stable nuclei with mass 5 or 8)

⇒ Prediction of BBN (big bang nucleosynthesis):

The "primordial" gas in the universe consists of 24% ^4He, 76% H (hydrogen) [Agrees very well with observations!]

⇒ strong evidence for Hot Big Bang

+ expansion (gives increasing T as $t \to 0$)

+ CMB (in microwaves, we "see" the Hot Big Bang!)