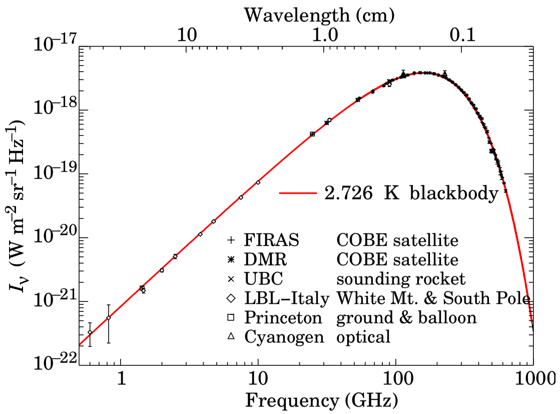
The Hot Big Bang

CMBR



(after Smoot, 1997, Fig. 1)

Penzias & Wilson (1965): "Measurement of Excess Antenna Temperature at 4080 Mc/s"
$\Longrightarrow$ Cosmic Microwave Background Radiation (CMBR)

The CMBR spectrum is fully consistent with a pure Planckian with temperature $T_{\text{CMBR}} = 2.728 \pm 0.004$ K: a relict of the hot big bang.

CMBR

Assumption: Early universe was hot and dense
$\Longrightarrow$ Equilibrium between matter and radiation.

Generation of radiation, e.g., in pair equilibrium,

$$\gamma + \gamma \longleftrightarrow \mathrm{e}^- + \mathrm{e}^+ \tag{10.1}$$

Equilibrium with electrons, e.g., via Compton scattering:

$$\mathrm{e}^- + \gamma \longrightarrow \mathrm{e}^- + \gamma \tag{10.2}$$

where the electrons are linked to protons via Coulomb interaction.

Once density low and temperature below photoionization for Hydrogen,

$$\mathrm{H} + \gamma \longleftrightarrow \mathrm{p} + \mathrm{e}^- \tag{10.3}$$

Decoupling of radiation and matter $\Longrightarrow$ Adiabatic cooling of photon field.

Proof for these assumptions, and lots of gory details: this and the next few lectures!

CMBR

Reminder: Planck formula for energy density of photons:

$$B_\lambda = \frac{\mathrm{d}u}{\mathrm{d}\lambda} = \frac{8\pi hc}{\lambda^5} \frac{1}{\exp(hc/k_\mathrm{B}T\lambda) - 1} \tag{10.4}$$

(units: erg cm^{-3} Å^{-1}), where

$$k_\mathrm{B} = 1.38 \times 10^{-16}\,\mathrm{erg\,K^{-1}} \quad \text{(Boltzmann)} \quad \text{and} \quad h = 6.625 \times 10^{-27}\,\mathrm{erg\,s} \quad \text{(Planck)} \tag{10.5}$$

For $\lambda \gg hc/k_\mathrm{B}T$: Rayleigh-Jeans formula:

$$B_\lambda \sim \frac{8\pi k_\mathrm{B}T}{\lambda^4} \tag{10.6}$$

(classical case, diverges for $\lambda \longrightarrow 0$, "Jeans catastrophe").

The wavelength of maximum emission is given by Wien's displacement law:

$$\lambda_{\max} = 0.201 \frac{hc}{k_\mathrm{B}T} \tag{10.7}$$

CMBR

The total energy density of the CMB is obtained by integration:

$$u = \int_0^\infty B_\lambda \, d\lambda = \frac{8\pi^5 (kT)^4}{15 h^3 c^3} = \frac{4\sigma_{SB}}{c} T^4 = a_{rad} T^4 \tag{10.8}$$

where

$$\sigma_{SB} = 5.670 \times 10^{-5}\,\mathrm{erg\,cm^{-3}\,K^{-4}} \quad \text{Stefan-Boltzmann} \tag{10.9}$$

$$a_{rad} = 7.566 \times 10^{-15}\,\mathrm{erg\,cm^{-2}\,K^{-4}\,s^{-1}} \quad \text{radiation density constant} \tag{10.10}$$

Since the energy of a photon is $E_\gamma = h\nu = hc/\lambda$, the total number density of photons is

$$n = \int_0^\infty \frac{B_\lambda \, d\lambda}{hc/\lambda} = 20.28\, T^3 \,\mathrm{photons\,cm^{-3}} \tag{10.11}$$

Thus, for today's CMBR:

$$n_{CMBR} = 400\,\mathrm{photons\,cm^{-3}} \tag{10.12}$$

CMBR

For the CMBR today:

$$n_{CMBR} = 400\,\mathrm{photons\,cm^{-3}} \tag{10.12}$$

Compare that to gravitating matter (protons for now).

$\Longrightarrow$ critical density:

$$\rho_c = \frac{3H^2}{8\pi G} = 1.88 \times 10^{-29} h^2\,\mathrm{g\,cm^{-3}} \hat{=} 1.13 \times 10^{-5}\, h^2\,\mathrm{protons\,cm^{-3}} \tag{8.42}$$

since $m_p = 1.67 \times 10^{-24}$ g.

$\Longrightarrow$ photons dominate the particle number:

$$\frac{n_{CMBR}}{n_{baryons}} = \frac{3.54 \times 10^7}{\Omega h^2} \tag{10.13}$$

$\Longrightarrow$ baryons dominate the energy density:

$$\frac{u_{CMBR}}{u_{baryons}} = \frac{a_{rad} T^4}{\Omega \rho_c c^2} = \frac{4.20 \times 10^{-13}}{1.69 \times 10^{-8}\,\Omega h^2} = \frac{1}{40260\,\Omega h^2} \tag{10.14}$$

That's why we talk about the matter dominated universe.

CMBR

But: The Universe was not always matter dominated:

Remember the scaling laws for the (energy) density of matter and radiation:

$$\begin{aligned}\rho_m &\propto R^{-3} \\ \rho_r &\propto R^{-4}\end{aligned} \quad \Longrightarrow \quad \frac{\rho_r}{\rho_m} \propto \frac{1}{R} \tag{8.63, 8.64}$$

$\Longrightarrow$ Photons dominate for large z, i.e., early in the universe!

Since $1 + z = R_0/R$ (Eq. 8.53), matter-radiation equality was at

$$1 + z_{eq} = 40260\,\Omega h^2 \tag{10.15}$$

(for $h = 0.75$, $1 + z_{eq} = 22650$)

The above definition of z_{eq} is not entirely correct: neutrino background, which increases the background energy density, is ignored ($u_\nu \sim 68\% u_\gamma$, see later).

Formally, matter-radiation equality defined from $n_{baryons} = n_{relativistic\ particles}$, giving

$$1 + z_{eq} = 23900\,\Omega h^2 \tag{10.16}$$

(for $h = 0.75$, $1 + z_{eq} = 13440$).

CMBR

What happened to the temperature of the CMBR?

Compare CMBR spectrum today with earlier times.

(Differential) Energy density in $[\lambda, \lambda + d\lambda]$:

$$du = B_\lambda d\lambda \tag{10.17}$$

Cosmological redshift:

$$\frac{\lambda'}{\lambda} = \frac{R'}{R} = \frac{1}{1+z} = a \tag{8.60}$$

Taking the expansion into account:

$$du' = \frac{du}{a^4} = \frac{8\pi hc}{a^4 \lambda^5} \frac{d\lambda}{\exp(hc/kT\lambda) - 1} = \frac{8\pi hc}{a^5 \lambda^5} \frac{a\,d\lambda}{\exp(hc/kT\lambda) - 1} = \frac{8\pi hc}{\lambda'^5} \frac{d\lambda'}{\exp(hca/kT\lambda') - 1} = B_{\lambda'}(T/a) \tag{10.18}$$

Therefore, the Planckian remains a Planckian, and the temperature of the CMBR scales as

$$T(z) = (1+z) T_0 \tag{10.19}$$

The early universe was hot $\Longrightarrow$ Hot Big Bang Model!

Overview

$a(t)$	t since BB	T[K] [K]	ρ_{matter} [g cm^{-3}]	Major Events
	10^{-42}	10^{30}		Planck era, "begin of physics"
	$10^{-40\ldots-30}$	10^{25}		Inflation?
10^{-13}	$\sim 10^{-5}$ s	$\sim 10^{13}$	$\sim 10^{9}$	generation of p-p^{-}, and baryon anti-baryon pairs from radiation background
3×10^{-9}	1 min	10^{10}	0.03	generation of e^{+}-e^{-} pairs out of radiation background
10^{-9}	10 min	3×10^{9}	10^{-3}	nucleosynthesis
$10^{-4}\ldots 10^{-3}$	$10^{6\ldots 7}$ yr	$10^{3\ldots 4}$	$10^{-21\ldots-18}$	End of radiation dominated epoch
7×10^{-4}	10^{7} yr	4000	10^{-20}	Hydrogen recombines, decoupling of matter and radiation
1	15×10^{9} yr	3	10^{-30}	now

Thermodynamics, I

Density in early universe is very high.

Physical processes (e.g., photon-photon pair creation, electron-positron annihilation etc.) all have reaction rates

$$\Gamma \propto n\sigma v \tag{10.20}$$

where

n: number density (cm^{-3})
σ: interaction cross-section (cm^{2})
v: velocity (cm s^{-1})

Thermodynamic equilibrium is reached if reaction rate much faster than "changes" in the system,

$$\Gamma \gg H \tag{10.21}$$

Where the Hubble parameter, H, is a good measure for (typical timescale of the Universe)$^{-1}$.

If thermodynamic equilibrium holds, then we can assume evolution of universe as sequence of states of local thermodynamic equilibrium, and use standard thermodynamics.

Before looking at real universe, first need to derive certain useful formulae from relativistic thermodynamics.

Thermodynamics, II

For ideal gases, thermodynamics shows that number density $f(\boldsymbol{p})\,\mathrm{d}p$ of particles with momentum in $[p, p+\mathrm{d}p]$ is given by

$$f(\boldsymbol{p}) = \frac{1}{\exp\left((E-\mu)/k_{\mathrm{B}}T\right) + a} \tag{10.22}$$

where

$$a = \begin{cases} +1 & : \text{Fermions (spin=1/2, 3/2,...)} \\ -1 & : \text{Bosons (spin=1, 2,...)} \\ 0 & : \text{Maxwell-Boltzmann} \end{cases}$$

and where the energy includes the rest-mass:

$$E^2 = |\boldsymbol{p}|^2 c^2 + m^2 c^4 \tag{10.23}$$

μ is called the "chemical potential". It is preserved in chemical equilibrium:

$$i + j \leftrightarrow k + l \quad\Longrightarrow\quad \mu_i + \mu_j = \mu_k + \mu_l \tag{10.24}$$

photons: multi-photon processes exist $\Longrightarrow \mu_\gamma = 0$.
particles in thermal equilibrium: $\mu = 0$ as well, because of the first law of thermodynamics,

$$\mathrm{d}E = T\,\mathrm{d}S - P\,\mathrm{d}V + \mu\,\mathrm{d}N \tag{10.25}$$

which, in equilibrium, is stationary with respect to changes in particle number N.

Thermodynamics, III

In addition to number density: different particles have internal degrees of freedom, g.

Examples:

photons: two polarization states $\Longrightarrow g = 2$
neutrinos: one polarization state $\Longrightarrow g = 1$
electrons, positrons: spin=1/2 $\Longrightarrow g = 2$

Knowing g and $f(p)$, it is possible to calculate interesting quantities:

particle number density: $$n = \frac{g}{(2\pi\hbar)^3}\int f(\boldsymbol{p})\,\mathrm{d}^3p \tag{10.26}$$

energy density: $$u = \rho c^2 = \frac{g}{(2\pi\hbar)^3}\int E(\boldsymbol{p})\,f(\boldsymbol{p})\,\mathrm{d}^3p \tag{10.27}$$

To calculate the pressure, remember that kinetic theory shows:

$$P = \frac{n}{3}\langle pv\rangle = \frac{n}{3}\left\langle \frac{p^2c^2}{E}\right\rangle \tag{10.28}$$

such that

$$P = \frac{g}{(2\pi\hbar)^3}\int \frac{p^2c^2}{3E}\,f(\boldsymbol{p})\,\mathrm{d}^3p \tag{10.29}$$

Thermodynamics, IV

Generally, we are interested in knowing n, u, and P in two limiting cases:

1. the ultra-relativistic limit, where $k_\mathrm{B}T \gg mc^2$, i.e., kinetic energy dominates the rest-mass
2. the non-relativistic limit, where $k_\mathrm{B}T \ll mc^2$

Transitions between these limits (i.e., what happens during "cooling") are usually much more complicated $\Longrightarrow$ ignore...

10–13

To derive the number density, the energy density, and the equation of state, note that Eq. (10.23) shows

$$E = \sqrt{p^2c^2 + m^2c^4} \tag{10.23}$$

such that

$$p = \sqrt{E^2 - m^2c^4}/c \tag{10.30}$$

Therefore

$$\frac{\mathrm{d}E}{\mathrm{d}p} = \frac{pc^2}{\sqrt{p^2c^2 + m^2c^4}} \tag{10.31}$$

from which it follows that

$$E\,\mathrm{d}E = pc^2\,\mathrm{d}p \tag{10.32}$$

Thus the following holds

$$\iiint_{-\infty}^{+\infty} \mathrm{d}^3p = \int_0^\infty 4\pi p^2\,\mathrm{d}p = \int_{mc^2}^\infty \frac{4\pi}{c^3}\left(E^2 - m^2c^4\right)^{1/2} E\,\mathrm{d}E \tag{10.33}$$

Going to a system of units where

$$c = k_\mathrm{B} = \hbar = 1 \tag{10.34}$$

to save me some typing, substitute these equations into Eqs. (10.26)–(10.29) to find

$$n = \frac{g}{2\pi^2}\int_m^\infty \frac{\left(E^2 - m^2\right)^{1/2} E\,\mathrm{d}E}{\exp\left((E-\mu)/T\right) \pm 1} \tag{10.35}$$

$$\rho = \frac{g}{2\pi^2}\int_m^\infty \frac{\left(E^2 - m^2\right)^{1/2} E^2\,\mathrm{d}E}{\exp\left((E-\mu)/T\right) \pm 1} \tag{10.36}$$

$$P = \frac{g}{6\pi^2}\int_m^\infty \frac{\left(E^2 - m^2\right)^{3/2}\,\mathrm{d}E}{\exp\left((E-\mu)/T\right) \pm 1} \tag{10.37}$$

which can in some limiting cases be expressed in a closed form (Kolb & Turner, 1990, eq. 3.52 ff., see following viewgraphs).

Thermodynamics, V

In the ultra-relativistic limit, $k_\mathrm{B}T \gg mc^2$, and assuming $\mu = 0$,

$$n = \begin{cases} \frac{\zeta(3)}{\pi^2}\, g \left(\frac{k_\mathrm{B}T}{\hbar c}\right)^3 & \text{Bosons} \\ \frac{3}{4}\frac{\zeta(3)}{\pi^2}\, g \left(\frac{k_\mathrm{B}T}{\hbar c}\right)^3 & \text{Fermions} \end{cases} \tag{10.38}$$

$$u = \begin{cases} \frac{\pi^2}{30}\, g\, k_\mathrm{B}T \left(\frac{k_\mathrm{B}T}{\hbar c}\right)^3 & \text{Bosons} \\ \frac{7}{8}\frac{\pi^2}{30}\, g\, k_\mathrm{B}T \left(\frac{k_\mathrm{B}T}{\hbar c}\right)^3 & \text{Fermions} \end{cases} \tag{10.39}$$

$$P = \rho c^2/3 = u/3 \tag{10.40}$$

where $\zeta(3) = 1.202\ldots$, and $\zeta(s)$ is Riemann's zeta-function (see handout, Eq. 10.48).

Eq. (10.40) is a simple result of the fact that in the relativistic limit, $E \sim pc$. Inserting this and $v = c$ into Eq. (10.28) gives the desired result.

As expected, we find the T^4 proportionality from the Stefan Boltzmann law!

10–14

Obtaining the previous formulae is an exercise in special functions. For example, the $T \gg m$, $T \gg \mu$ case for ρ for Bosons (Eq. 10.39) is obtained as follows (setting $c = k_\mathrm{B} = \hbar = 1$):

$$\rho_\mathrm{Boson} = \frac{g}{2\pi^2}\int_m^\infty \frac{\left(E^2 - m^2\right)^{1/2} E^2\,\mathrm{d}E}{\exp\left((E-\mu)/T\right) \pm 1} \tag{10.41}$$

because of $T \gg \mu$

$$\approx \frac{g}{2\pi^2}\int_m^\infty \frac{\left(E^2 - m^2\right)^{1/2} E^2\,\mathrm{d}E}{\exp(E/T) \pm 1} \tag{10.42}$$

for *Bosons*, choose -1, and substitute $x = E/T$:

$$= \frac{g}{2\pi^2}\int_{m/T}^\infty \frac{\left(x^2T^2 - m^2\right)^{1/2} x^2T^3\,\mathrm{d}x}{\exp(x) - 1} \tag{10.43}$$

Since $T \gg m$,

$$\approx \frac{g}{2\pi^2}\int_0^\infty \frac{x^3T^4\,\mathrm{d}x}{\exp(x) - 1} \tag{10.44}$$

$$= \frac{gT^4}{2\pi^2}\int_0^\infty \frac{x^3\,\mathrm{d}x}{\exp(x) - 1} \tag{10.45}$$

$$= \frac{gT^4}{2\pi^2}\cdot 6\zeta(4) \tag{10.46}$$

$$= \frac{\pi^2}{30} gT^4 \tag{10.47}$$

where $\zeta(s)$ is *Riemann's zeta-function*, which is defined by (Abramowitz & Stegun, 1964)

$$\zeta(s) = \frac{1}{\Gamma(s)}\int_0^\infty \frac{x^{s-1}}{\exp(x) - 1}\,\mathrm{d}x \quad \text{for } \mathscr{R}e\, s > 1 \tag{10.48}$$

where $\Gamma(x)$ is the Gamma-function. Note that $\zeta(4) = \pi^4/90$.

For *Fermions*, everything is the same except for that we now have to choose the $+$ sign. The equivalent of Eq. (10.45) is then

$$\rho_{\text{Fermi}} = \frac{gT^4}{2\pi^2}\int_0^\infty \frac{x^3\,\mathrm{d}x}{\exp(x)+1} \tag{10.49}$$

Now we can make use of formula 3.411.3 of Gradstein & Ryshik (1981),

$$\int_0^\infty \frac{x^{\nu-1}\,\mathrm{d}x}{\exp(\mu x)+1} = \frac{1}{\mu^\nu}(1-2^{1-\nu})\Gamma(\nu)\zeta(\nu) \quad \text{for } \mathscr{Re}\,\mu,\nu>1 \tag{10.50}$$

to see where the additional factor of $7/8$ in Eq. (10.39) comes from.

Thermodynamics, VI

In the non-relativistic limit: $k_\text{B}T \ll mc^2$

$\Longrightarrow$ we can ignore the ± 1 term in the denominator

$\Longrightarrow$ Same formulae for Bosons and Fermions!

$$n = \frac{2g}{(2\pi\hbar)^3}(2\pi m k_\text{B}T)^{3/2}\mathrm{e}^{-mc^2/k_\text{B}T} \tag{10.51}$$

$$u = nmc^2 \tag{10.52}$$

$$P = nk_\text{B}T \tag{10.53}$$

Therefore:

- energy density dominated by rest-mass ($\rho = u/c^2 = mn$)
- $P \ll \rho c^2/3$, i.e., *much* smaller than for relativistic particles

  $\Longrightarrow$ Particle pressure is only important for relativistic particles

Obviously, relativistic particles with $m=0$ (or very close to 0) will never become nonrelativistic. Still, they can "decouple" from the rest of the universe when their interaction rates go to 0.

Equation of State

Pressure of ultra-relativistic particles $\gg$ Pressure of nonrelativistic particles

$\Longrightarrow$ Nonrelativistic particles unimportant for equation of state.

For relativistic particles:

$$u_\text{bosons} = \frac{\pi^2}{30}\,g\,k_\text{B}T\left(\frac{k_\text{B}T}{\hbar c}\right)^3 \quad\text{and}\quad u_\text{fermions} = \frac{7}{8}u_\text{bosons} \tag{10.39}$$

$\Longrightarrow$ Total energy density for mixture of particles is sum over all particles, written as

$$u = g_*\cdot\frac{\pi^2}{30}k_\text{B}T\left(\frac{k_\text{B}T}{\hbar c}\right)^3 \tag{10.54}$$

where the effective degeneracy factor

$$g_* = \sum_\text{bosons} g_\text{B}\left(\frac{T_\text{B}}{T}\right)^4 + \frac{7}{8}\sum_\text{fermions} g_\text{F}\left(\frac{T_\text{F}}{T}\right)^4 \tag{10.55}$$

g_* counts total number of internal degrees of freedom of *all* relativistic bosonic and fermionic species, i.e., all relativistic particles which are in thermodynamic equilibrium

The pressure is obtained from Eq. (10.54) as $P = u/3$.

Early Expansion, I

Knowing the equation of state, we can now use the Friedmann equations to determine the early evolution of the universe.

Friedmann:

$$\dot{R}^2 = \frac{8\pi G}{3}\rho R^2 - kc^2 \tag{8.39}$$

or, dividing by R^2,

$$\frac{\dot{R}^2}{R^2} = H(t)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{R^2} \tag{8.40}$$

But: The early universe is dominated by relativistic particles

$\Longrightarrow$ $\rho \propto R^{-4}$

$\Longrightarrow$ Density-term dominates

$\Longrightarrow$ we can set $k=0$.

Early universe is asymptotically flat!

This will prove to be one of the most crucial problems of modern cosmology...

Early Expansion, II

The Friedmann equations show the evolution of the early Universe:

Since $\rho \propto R^{-4}$ (relativistic background),

$$\rho = \rho_0 \left(\frac{R_0}{R}\right)^4 \qquad (10.56)$$

Friedmann's equation then is

$$\frac{\mathrm{d}R}{\mathrm{d}t} = \sqrt{\frac{8\pi G\rho}{3}}R = \sqrt{\frac{8\pi G\rho_0}{3}}\frac{R_0^2}{R} \implies \frac{\mathrm{d}a}{\mathrm{d}t} = \sqrt{\frac{8\pi G\rho_0}{3}}\frac{1}{a} =: \xi a^{-1} \qquad (10.57)$$

where $a = R/R_0$.

Separation of variables gives

$$\int_0^{a(t)} a\,\mathrm{d}a = \int_0^t \xi\,\mathrm{d}t \implies a(t) = \xi^{1/2}\cdot t^{1/2} \qquad (10.58)$$

Therefore, for $k = 0$ the Hubble constant evolves as

$$H(t) = \frac{\dot a}{a} = \frac{1}{2t} \qquad (10.59)$$

Early Expansion, III

Using the equation of state from Eq. 10.54, we can relate $H(t)$ to the temperature.

Inserting Eq. 10.54) into Friedmann's equation gives

$$\left(\frac{\dot R}{R}\right)^2 = H^2(t) = \frac{8\pi G\rho}{3} = \frac{8\pi G}{3} g_* \frac{\pi^2}{30}\frac{(k_\mathrm{B}T)^4}{(\hbar c)^3} = \frac{4\pi^3 G}{45(\hbar c)^3} g_* (k_\mathrm{B}T)^4 \qquad (10.60)$$

and with Eq. 10.59:

$$H(t) = \left(\frac{4\pi^3 G}{45(\hbar c)^3}\right)^{1/2} g_*^{1/2} (k_\mathrm{B}T)^2 = \frac{1}{2t} \qquad (10.61)$$

Solving for t gives the time-temperature relationship:

$$t = \left(\frac{45(\hbar c)^3}{16\pi^3 G}\right)^{1/2} \frac{1}{g_*^{1/2}}\frac{1}{(k_\mathrm{B}T)^2} \qquad (10.62)$$

Inserting all constants and converting to more useful units gives

$$t = \frac{2.4\,\mathrm{s}}{g_*^{1/2}}\cdot\left(\frac{k_\mathrm{B}T}{1\,\mathrm{MeV}}\right)^{-2} \qquad (10.63)$$

. . . one of the most useful equations for the early universe.

Elementary Particles

Behavior of universe depends on $g_* \implies$ Strong dependency on elementary particle physics.

Generally, particles present when energy in other particles allows generation of particle–antiparticle pairs, i.e., when $k_\mathrm{B}T \gtrsim mc^2$ (threshold temperature)

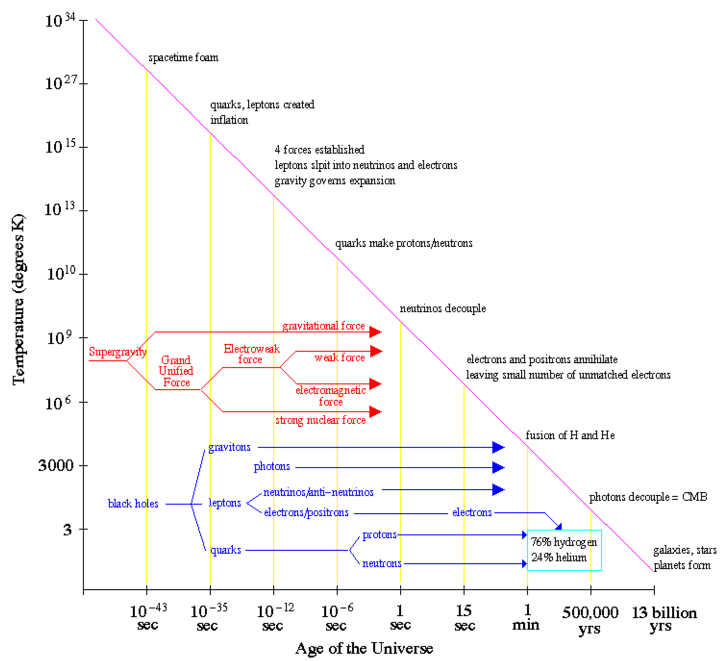
Current particle physics provides the following picture:

Temp.	New Particles	$4g_*$
$k_\mathrm{B}T < m_\mathrm{e}c^2$	γ's and ν's	29
$m_\mathrm{e}c^2 < k_\mathrm{B}T < m_\mu c^2$	$e^\pm$	43
$m_\mu c^2 < k_\mathrm{B}T < m_\pi c^2$	$\mu^\pm$	57
$m_\pi c^2 < k_\mathrm{B}T < k_\mathrm{B}T_\mathrm{c}$	π's	69
$k_\mathrm{B}T_\mathrm{c} < k_\mathrm{B}T < m_\mathrm{strange}c^2$	$-\pi$'s+u, $\bar{\mathrm{u}}$, d, $\bar{\mathrm{d}}$, gluons	205
$m_\mathrm{s}c^2 < k_\mathrm{B}T < m_\mathrm{charm}c^2$	s, $\bar{\mathrm{s}}$	247
$m_\mathrm{c}c^2 < k_\mathrm{B}T < m_\tau c^2$	c, $\bar{\mathrm{c}}$	289
$m_\tau c^2 < k_\mathrm{B}T < m_\mathrm{bottom}c^2$	$\tau^\pm$	303
$m_\mathrm{b}c^2 < k_\mathrm{B}T < m_\mathrm{W,Z}c^2$	b, $\bar{\mathrm{b}}$	345
$m_\mathrm{W,Z}c^2 < k_\mathrm{B}T < m_\mathrm{top}c^2$	$W^\pm$, Z	381
$m_\mathrm{t}c^2 < k_\mathrm{B}T < m_\mathrm{Higgs}c^2$	t, $\bar{\mathrm{t}}$	423
$m_\mathrm{Higgs}c^2 < k_\mathrm{B}T$	H^0	427

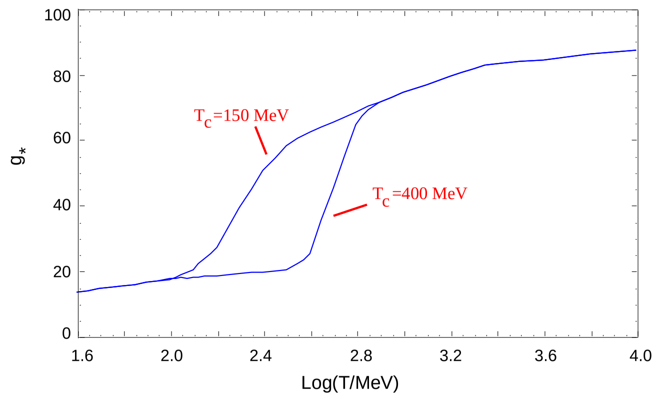
$k_\mathrm{B}T_\mathrm{c}$: energy of confinement-deconfinement for transitions quarks $\implies$ hadrons, somewhere between 150 MeV and 400 MeV.

Example: photons (2 polarization states, i.e., $g = 2$) and three species of neutrinos ($g = 1$, but with distinguishable anti-particles) $\implies g_* = 2 + (7/8)\cdot 2\cdot 3 = 58/8 = 29/4$.

(Olive, 1999, Tab. 1)



Elementary Particles



(Olive, 1999, Fig. 1)

Will now consider times when only Neutrinos and Electron/Positrons present (after baryogenesis, see next lecture for that).

Interlude

Previous (abstract) formulae allow to estimate quantities like

1. The existence and energy of primordial neutrinos,
2. The formation of neutrons,
3. The formation of heavier elements.

Detailed computations require solving nonlinear differential equations

$\Longrightarrow$ difficult, only numerically possible.

Essentially, need to self-consistently solve Boltzmann equation in expanding universe for evolution of phase space density with time, using the correct QCD/QED reaction rates $\Longrightarrow$ too complicated (at least for me...).

Will use approximate analytical way here, which gives surprisingly exact answers.

Neutrinos, I

Neutrino equilibrium caused by weak interactions such as

$$\mathrm{e}^- + \mathrm{e}^+ \longleftrightarrow \nu + \bar{\nu} \quad \text{or} \quad \mathrm{e}^- + \nu \longleftrightarrow \mathrm{e}^- + \nu \quad \text{etc.} \qquad (10.64)$$

Reaction rate for these processes:

$$\Gamma = n \langle \sigma v \rangle \qquad (10.65)$$

where the thermally averaged interaction cross-section is

$$\langle \sigma v \rangle \approx \left\langle \frac{\alpha^2 p}{m_\mathrm{W}^4} \cdot p \right\rangle \sim 10^{-2} \frac{(k_\mathrm{B} T)^2}{m_\mathrm{W}^4} \qquad (10.66)$$

m_W: mass of W-boson (exchange particle of weak interaction), $\alpha \approx 1/137$: fine structure constant.

But in the ultra-relativistic limit, $n \propto T^3$ (Eq. 10.38), such that

$$\Gamma_\mathrm{weak} \propto \frac{\alpha^2 T^5}{m_\mathrm{W}^4} \qquad (10.67)$$

Neutrinos, II

Because of Eqs. (10.59) and (10.62), the temperature dependence of the Hubble constant is

$$H(T) = 1.66 g_*^{1/2} \cdot \frac{T^2}{m_\mathrm{P}} \qquad (10.68)$$

where m_P is the Planck mass, $m_\mathrm{P} c^2 = 1.22 \times 10^{19}$ GeV (see later, Eq. 11.24).

Neutrino equilibrium possible as long as $\Gamma_\mathrm{weak} > H$, i.e., (inserting exact numbers)

$$k_\mathrm{B} T_\mathrm{dec} \gtrsim \left(\frac{500\, c^6\, m_\mathrm{W}^4}{m_\mathrm{P}} \right)^{1/3} \sim 1\,\mathrm{MeV} \qquad (10.69)$$

Neutrinos decouple ~ 1 s after the big bang.

This follows from Eq. (10.63), remembering that for this phase, $g_* \sim 10$.

Since decoupling, primordial neutrinos just follow expansion of universe, virtually no interaction with "us" anymore.

Entropy, I

The entropy of particles is defined through

$$S = \frac{E+PV}{T} \qquad (10.70)$$

Important for cosmology: relativistic limit. Define the entropy density,

$$s = \frac{S}{V} = \frac{E/V+P}{T} = \frac{u+P}{T} \approx \frac{4}{3}\frac{u}{T} \qquad (10.71)$$

(last step for relativistic limit; Eq. 10.40)

Inserting Eq. (10.39) ($u \propto (7/8)T^4$; 7/8 for Fermions only) gives

$$s = \frac{7}{8}\frac{2\pi^2}{45} g k_B \left(\frac{k_B T}{\hbar c}\right)^3 = \frac{7}{8}\frac{2\pi^4}{45\,\zeta(3)} k_B\, n \qquad (10.72)$$

Since $s \propto n$ for backgrounds, the parameter $\eta = n_{\text{CMBR}}/n_{\text{baryons}}$ is often called the "entropy per baryon".

Entropy, II

For a mixture of backgrounds, Eq. (10.72) gives

$$\frac{s}{k_B} = g_{*,S} \cdot \frac{2\pi^2}{45}\left(\frac{k_B T}{\hbar c}\right)^3 \qquad (10.73)$$

where $g_{*,S}$ is the analogue to g_* (Eq. 10.55),

$$g_{*,S} = \sum_{\text{bosons}} g_B \left(\frac{T_B}{T}\right)^3 + \frac{7}{8}\sum_{\text{fermions}} g_F \left(\frac{T_F}{T}\right)^3 \qquad (10.74)$$

Note that if the species are not at the same temperature, $g_* \neq g_{*,S}$.

Entropy per mass today:

$$\frac{S}{M} = \frac{10^{16}}{\Omega h^2}\,\text{erg}\,\text{K}^{-1}\,\text{g}^{-1} \qquad (10.75)$$

while the entropy gain of heating water at 300 K by 1 K is $\sim 1.4 \times 10^5\,\text{erg}\,\text{K}^{-1}\,\text{g}^{-1}$.

$\Longrightarrow$ "Human attempts to obey 2nd law ... are swamped by ... microwave background" (Peacock, 1999, p. 277).

$\Longrightarrow$ $S =$ const. for universe to very good approximation.

$\Longrightarrow$ Universe expansion is adiabatic!

Reheating

After decoupling of neutrinos, neutrino distribution just gets redshifted (similar to CMBR, Eq. 10.19):

$$\frac{T_\nu}{T_{\text{dec}}} = \frac{R_{\text{dec}}}{R(t)} \Longrightarrow T_\nu \propto R^{-1} \qquad (10.76)$$

On the other hand, the temperature of the universe is

$$T \propto g_{*,S}^{1/3} R^{-1} \qquad (10.77)$$

This follows from $S/V \propto T^3$ (Eq. 10.73), $V \propto R^3$, and $S =$ const. (adiabatic expansion of the universe).

$\Longrightarrow$ as long as $g_{*,S} =$ const. we have $T_\nu = T$

$\Longrightarrow$ Immediately after decoupling, neutrino background appears as if it is still in equilibrium.

However: Temperature at neutrino decoupling is $\sim 2m_e c^2$. But, for $kT_{\text{BB}} < 2\,m_e c^2$, pair creation,

$$\gamma + \gamma \longleftrightarrow e^- + e^+ \qquad (10.78)$$

is kinematically impossible.

$\Longrightarrow$ Shortly after neutrino decoupling: $e^\pm$ annihilation

$\Longrightarrow$ $g_{*,S}$ changes!

$\Longrightarrow$ We expect that $T_{\text{CMBR}} \neq T_\nu$.

Reheating

Difference in $g_{*,S}$:

- before annihilation: e^-, e^+, $\gamma \Longrightarrow g_{*,S} = 2 + 2\cdot 2\cdot(7/8) = 11/2$.
- after annihilation: $\gamma \Longrightarrow g_{*,S} = 2$

But: the total entropy for particles in equilibrium is conserved ("expansion is adiabatic"):

$$g_{*,S}(T_{\text{before}}) \cdot T^3_{\text{before}} = g_{*,S}(T_{\text{after}}) \cdot T^3_{\text{after}} \qquad (10.79)$$

such that

$$T_{\text{after}} = \left(\frac{11}{4}\right)^{1/3} T_{\text{before}} \sim 1.4 \cdot T_{\text{before}} \qquad (10.80)$$

Since $T_{\text{after}} > T_{\text{before}}$: "reheating".

Note that in reality the annihilation is not instantaneous and T decreases (albeit less rapidly) during "reheating"...

$\Longrightarrow$ Since neutrino-background does not "see" annihilation it just continues to cool

$\Longrightarrow$ current temperature of neutrinos is

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_{\text{CMBR}} \sim 1.95\,\text{K} \qquad (10.81)$$

History

After reheating: universe consists of p, n, γ (and e^- to preserve charge neutrality)

$\Longrightarrow$ Ingredients for Big Bang Nucleosynthesis (BBN).

Historical perspective: Cross section to make Deuterium:

$$\langle\sigma v\rangle(\mathrm{p}+\mathrm{n}\to\mathrm{D}+\gamma)\sim 5\times 10^{-20}\,\mathrm{cm^3\,s^{-1}} \tag{10.82}$$

Furthermore, we need temperatures of $T_{\mathrm{BBN}}\sim 100\,\mathrm{keV}$, i.e., $t_{\mathrm{BBN}}\sim 200\,\mathrm{s}$ (Eq. 10.63).

By Eq. (10.20) this implies a particle density of

$$n\sim\frac{1}{\langle\sigma v\rangle\cdot t_{\mathrm{BBN}}}\sim 10^{17}\,\mathrm{cm^{-3}} \tag{10.83}$$

Today: Baryon density $n_{\mathrm{B}}\sim 10^{-7}\,\mathrm{cm^{-3}}$. Since $n\propto R^{-3}$,

$$T(\mathrm{today})=\left(\frac{n_{\mathrm{B}}}{n}\right)^{1/3}\cdot T_{\mathrm{BBN}}\sim 10\,\mathrm{K} \tag{10.84}$$

pretty close to the truth...

The above discussion was first asserted by George Gamov and coworkers in 1948, and was the first prediction of the cosmic microwave background radiation!

Observations: BBN is required by observations, since no other production region for Deuterium known, and since He-abundance $\sim$ 25% by mass everywhere.

Proton/Neutron, I

Initial conditions for BBN: Set by Proton-Neutron-Ratio.

For $t\ll 1\,\mathrm{s}$, equilibrium via weak interactions:

$$\begin{aligned}\mathrm{n}&\longleftrightarrow p+\mathrm{e}^-+\bar\nu_{\mathrm{e}}\\ \nu_{\mathrm{e}}+\mathrm{n}&\longleftrightarrow p+\mathrm{e}^-\\ \mathrm{e}^++\mathrm{n}&\longleftrightarrow p+\bar\nu_{\mathrm{e}}\end{aligned} \tag{10.85}$$

Reactions fast as long as particles relativistic.

But once $T\sim 1\,\mathrm{MeV}$: n, p become non-relativistic

$\Longrightarrow$ Boltzmann statistics applies (or use Eq. 10.51):

$$\frac{n_{\mathrm{n}}}{n_{\mathrm{p}}}=\mathrm{e}^{-\Delta mc^2/k_{\mathrm{B}}T}=\mathrm{e}^{-1.3\,\mathrm{MeV}/k_{\mathrm{B}}T} \tag{10.86}$$

$\Longrightarrow$ Suppression of n with respect to p because of larger mass ($m_{\mathrm{n}}c^2=939.57\,\mathrm{MeV}$, $m_{\mathrm{p}}c^2=938.27\,\mathrm{MeV}$)

Proton/Neutron, II

As usual, the n, p abundance freezes out when $\Gamma\gg H$.

For the neutron, proton equilibrium, the reaction rate is

$$\Gamma(\nu_{\mathrm{e}}+\mathrm{n}\leftrightarrow\mathrm{p}+\mathrm{e}^-)\sim 2.1\left(\frac{T}{1\,\mathrm{MeV}}\right)^5\,\mathrm{s}^{-1} \tag{10.87}$$

The neutron abundance freezes out at $k_{\mathrm{B}}T\sim 0.8\,\mathrm{MeV}$ ($t=1.7\,\mathrm{s}$), such that $n_{\mathrm{n}}/n_{\mathrm{p}}=0.2$

After that: Neutron decay ($\tau_{\mathrm{n}}=886.7\pm 1.2\,\mathrm{s}$).

$\Longrightarrow$ Nucleosynthesis has to be over before neutrons are decayed away!

$\Longrightarrow$ Nucleosynthesis only takes a few minutes at most!

Deuterium

The first step in nucleosynthesis is the formation of deuterium (binding energy $E_{\mathrm{B}}=2.225\,\mathrm{MeV}$, i.e., $1.7(m_{\mathrm{n}}-m_{\mathrm{p}})c^2$):

$$\mathrm{p}+\mathrm{n}\longleftrightarrow\mathrm{D}+\gamma \tag{10.88}$$

Note: Both fusion and photodisintegration are possible:

$$\Gamma_{\mathrm{fusion}}=n_{\mathrm{B}}\langle\sigma v\rangle \tag{10.89}$$

$$\Gamma_{\mathrm{photo}}=n_\gamma\langle\sigma v\rangle\mathrm{e}^{-E_{\mathrm{B}}/k_{\mathrm{B}}T} \tag{10.90}$$

At first: photodisintegration dominates since $\eta^{-1}=n_\gamma/n_{\mathrm{B}}\sim 10^{10}$ (see Eq. 10.72).

Build up of D is only possible once $\Gamma_{\mathrm{fusion}}>\Gamma_{\mathrm{photo}}$, i.e., when

$$\frac{n_\gamma}{n_{\mathrm{B}}}\mathrm{e}^{-E_{\mathrm{B}}/k_{\mathrm{B}}T}\sim 1 \tag{10.91}$$

Inserting numbers shows that

Deuterium production starts at $k_{\mathrm{B}}T\sim 100\,\mathrm{keV}$, or $t\sim 100\,\mathrm{s}$.

Heavier Elements, I

Once deuterium present:

nucleosynthesis of lighter elements:

$$\begin{aligned} \mathrm{D}+\mathrm{D} &\longrightarrow \mathrm{T}+\mathrm{p} \\ \mathrm{D}+\mathrm{n} &\longrightarrow \mathrm{T}+\gamma \\ \mathrm{D}+\mathrm{p} &\longrightarrow {}^{3}\mathrm{He}+\gamma \\ \mathrm{D}+\mathrm{D} &\longrightarrow {}^{3}\mathrm{He}+\mathrm{n} \\ {}^{3}\mathrm{He}+\mathrm{n} &\longrightarrow \mathrm{T}+\mathrm{p} \end{aligned} \tag{10.92}$$

production of ^{4}He:

$$\begin{aligned} \mathrm{D}+\mathrm{D} &\longrightarrow {}^{4}\mathrm{He}+\gamma \\ \mathrm{D}+{}^{3}\mathrm{He} &\longrightarrow {}^{4}\mathrm{He}+\mathrm{p} \\ \mathrm{T}+\mathrm{D} &\longrightarrow {}^{4}\mathrm{He}+\mathrm{n} \\ {}^{3}\mathrm{He}+{}^{3}\mathrm{He} &\longrightarrow {}^{4}\mathrm{He}+2\mathrm{p} \\ \mathrm{T}+\mathrm{p} &\longrightarrow {}^{4}\mathrm{He}+\gamma \\ {}^{3}\mathrm{He}+\mathrm{n} &\longrightarrow {}^{4}\mathrm{He}+\gamma \end{aligned} \tag{10.93}$$

Heavier Elements, II

Element gap at $A = 5$ can be overcome to produce Lithium:

$$\begin{aligned} {}^{3}\mathrm{He}+{}^{4}\mathrm{He} &\longrightarrow {}^{7}\mathrm{Be}+\gamma \\ {}^{7}\mathrm{Be} &\longrightarrow {}^{7}\mathrm{Li}+\mathrm{e}^{+}+\nu_{\mathrm{e}} \\ \mathrm{T}+{}^{4}\mathrm{He} &\longrightarrow {}^{7}\mathrm{Li}+\mathrm{e}^{+}+\nu_{\mathrm{e}} \end{aligned} \tag{10.94}$$

Gap at $A = 8$ prohibits production of heavier isotopes.

⟹ Major product of BBN: ^{4}He.

Mass fraction of ^{4}He can be estimated assuming all neutrons incorporated into ^{4}He

⟹ number density of H=number of remaining protons, i.e., mass fraction

$$X = \frac{n_\mathrm{p} - n_\mathrm{n}}{n_\mathrm{p} + n_\mathrm{n}} \tag{10.95}$$

and

$$Y = 1 - \frac{n_\mathrm{p} - n_\mathrm{n}}{n_\mathrm{p} + n_\mathrm{n}} = 2\left(1 + \frac{n_\mathrm{p}}{n_\mathrm{n}}\right)^{-1} \tag{10.96}$$

Because of neutron decay, at $k_\mathrm{B}T = 0.8\,\mathrm{MeV}$: $n_\mathrm{n}/n_\mathrm{p} = 1/7$, such that

BBN predicts primordial He-abundance of $Y = 0.25$.

Remarkable Things

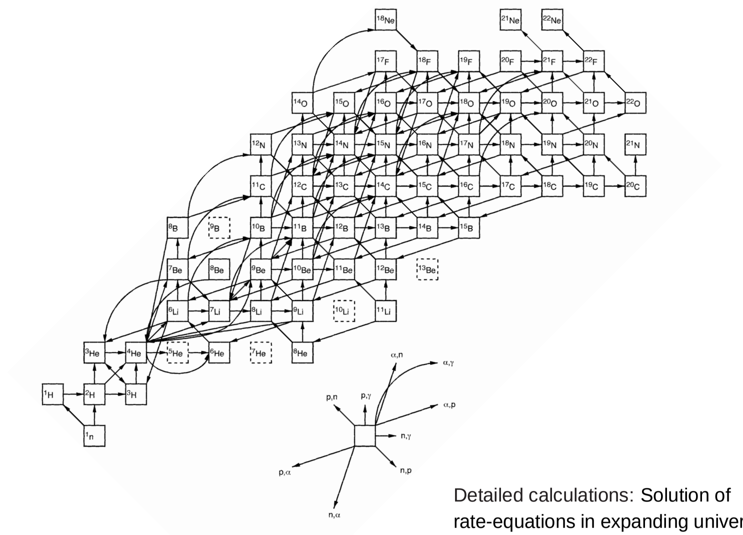
Note the following coincidences:

1. Freeze out of nucleons simultaneous to freeze out of neutrinos.
2. . . . and parallel to electron-positron annihilation.
3. Expansion is slow enough that neutrons can be bound to nuclei.

⟹ Long chain of coincidences makes our current universe possible!

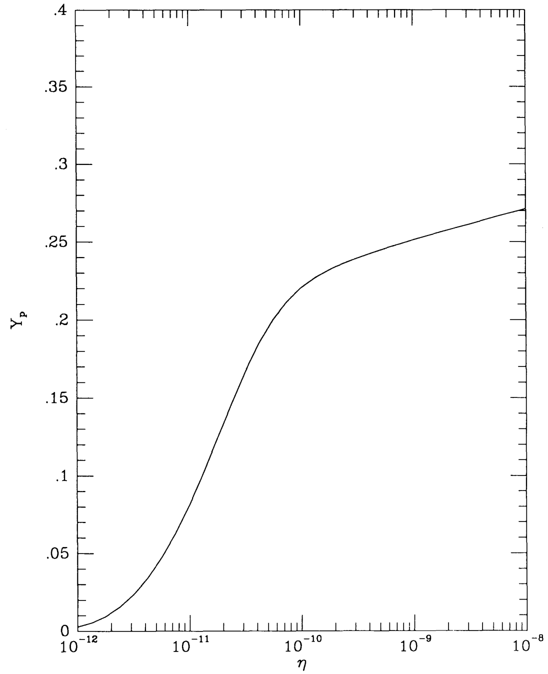
Detailed Calculations, I

1. Generally, BBN operates as a function of the entropy per baryon, η.
   Remember that the entropy density for a baryon is
   $$s = \frac{7}{8}\frac{2\pi^2}{45} g k_\mathrm{B} \left(\frac{k_\mathrm{B}T}{\hbar c}\right)^3 = \frac{7}{8}\frac{2\pi^4}{45\,\zeta(3)} k_\mathrm{B}\, n \tag{10.72}$$
   and therefore the entropy per baryon is
   $$\eta = \frac{n_\mathrm{CMBR}}{n_\mathrm{baryons}} \tag{10.97}$$
   Note that η is related to Ω in baryons, Ω_B:
   $$\Omega_\mathrm{B} = 3.67 \times 10^7 \cdot \eta \tag{10.98}$$
   (since η, Ω determine expansion behavior)
   ⟹ Perform computations as function of η!
2. Since Y is set by $n_\mathrm{p}/n_\mathrm{n}$
   ⟹ He abundance is relatively independent from η



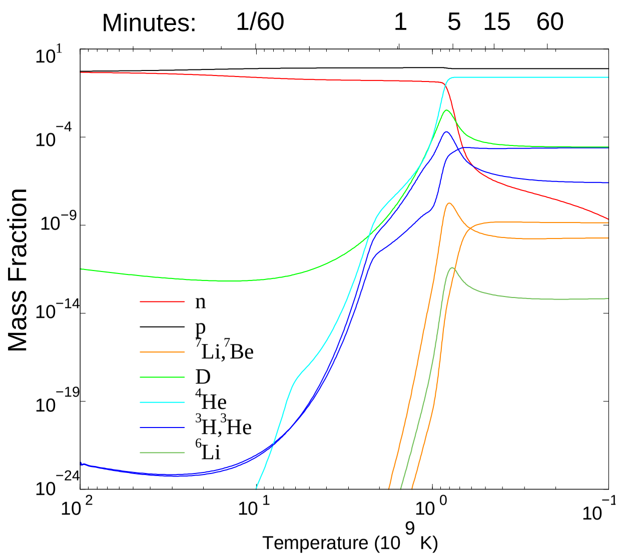
(Olive, 1999, Fig. 3)

Detailed calculations: Solution of rate-equations in expanding universe, see, e.g., Wagoner, Fowler & Hoyle (1967), Thomas et al. (1993), Olive (1999), Tytler et al. (2000), and Kneller & Steigman (2004).

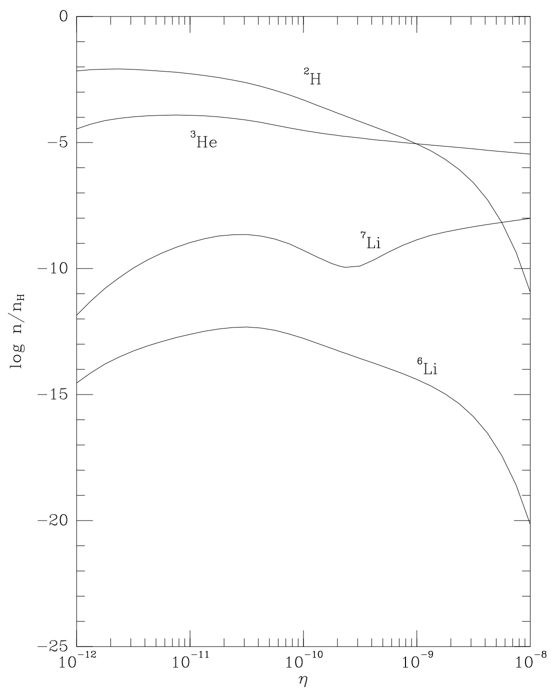


He abundance as function of η (Thomas et al., 1993, Fig. 3a)

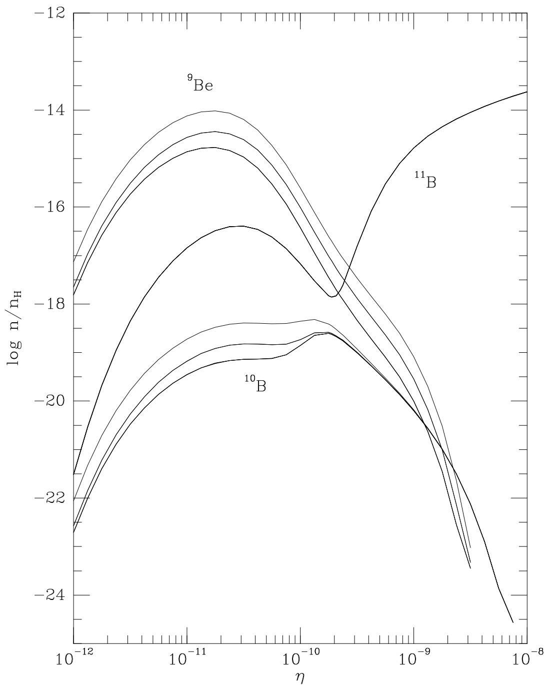
Detailed Calculations, III



Build-up of abundances as function of time for $\eta = 5.1 \times 10^{-10}$ (Burles, Nollett & Turner, 1999, Fig. 3), remember: $\eta = n_{\mathrm{CMBR}}/n_{\mathrm{baryons}}$



Light-element abundances as function of η (Olive, 1999, Fig. 4)



Intermediate mass abundances as function of η (Olive, 1999, Fig. 5)

Confrontation with WMAP

As we will see later: fluctuations in cosmic microwave background allow for a tight determination of cosmological parameters.

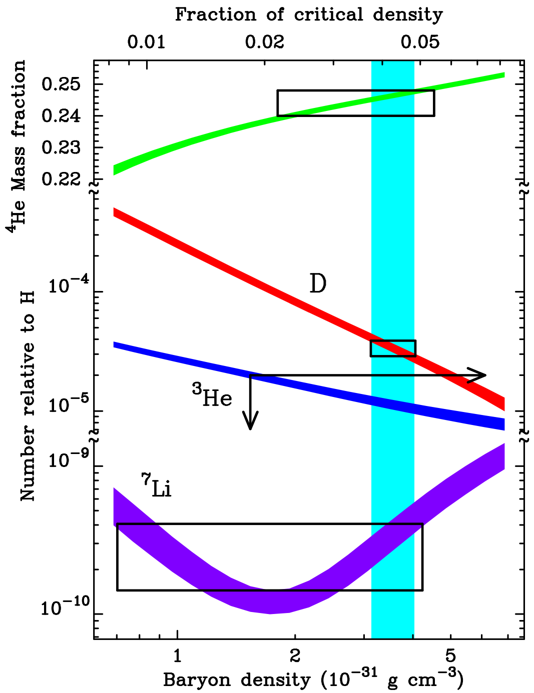
Best results so far from Wilkinson Microwave Anisotropy Probe (WMAP; see Spergel et al. 2007):

$$\Omega_b h^2 = 0.02233^{+0.00072}_{-0.00091} \tag{10.99}$$

With the most modern BBN calculations (Kneller & Steigman, 2004), this gives (Molaro, 2007):

Element	SBBN+WMAP
Y_p	$0.2482^{+0.0004}_{-0.0003}$
^{3}He/H	$(10.5 \pm 0.6) \times 10^{-6}$
D/H	$(25.7^{+1.7}_{-1.3}) \times 10^{-6}$
Li/H	$(4.41^{+0.3}_{-0.4}) \times 10^{-10}$

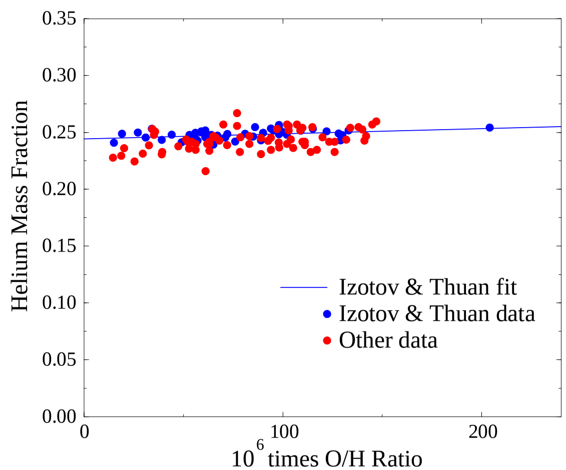
$\Longrightarrow$ Can use WMAP parameters and BBN theory to compare BBN theory with measurements



BBN observations strongly constrain Ω_{Baryons}.

(Burles, Nollett & Turner, 1999, Fig. 1)

^{4}He



(Burles, Nollett & Turner, 1999, Fig. 4)

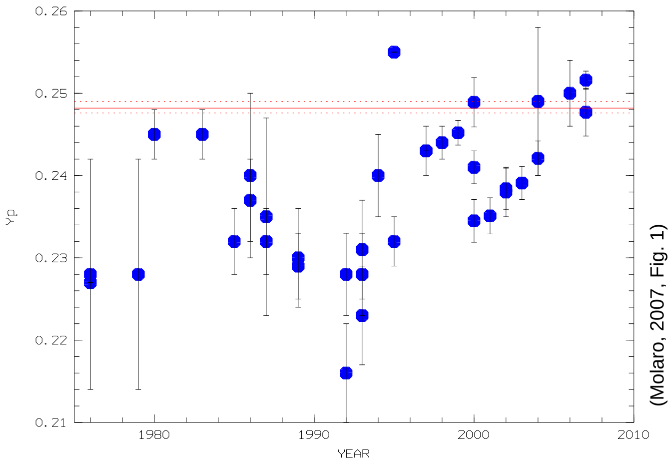
^{4}He produced in stars
$\Longrightarrow$ extrapolate to zero metallicity in systems of low metallicity (i.e., minimize stellar processing).

Best determination from He II$\longrightarrow$He I recombination lines in H II regions (metallicity $\sim 20\%$ solar).

Result: Linear correlation He vs. O
$\Longrightarrow$ extrapolate to zero oxygen to obtain primordial abundances.

Result: $Y = 0.234 \pm 0.005$ (Olive, 1999).

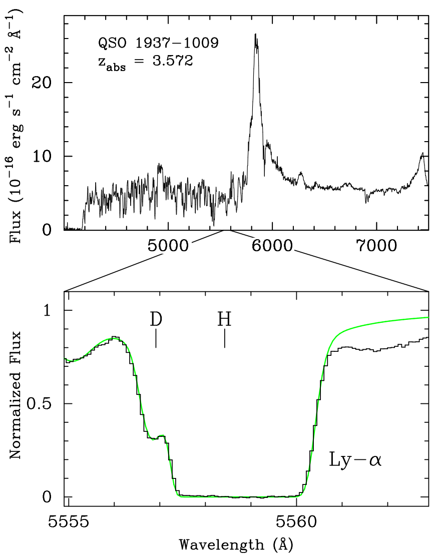
WMAP BBN and He



(Molaro, 2007, Fig. 1)

After improving He recombination physics and intrinsic absorption, He abundances are now in agreement with BBN prediction using Ω_B from WMAP.

Deuterium, I



Stars destroy D in fusion processes

$\Longrightarrow$ use as non-processed material as possible!

Lyα forest: absorption of quasar light by intervening material

$\Longrightarrow$ Some absorption lines in the Lyα forest show asymmetric line structure caused by primordial deuterium.

Remember the Balmer formula:

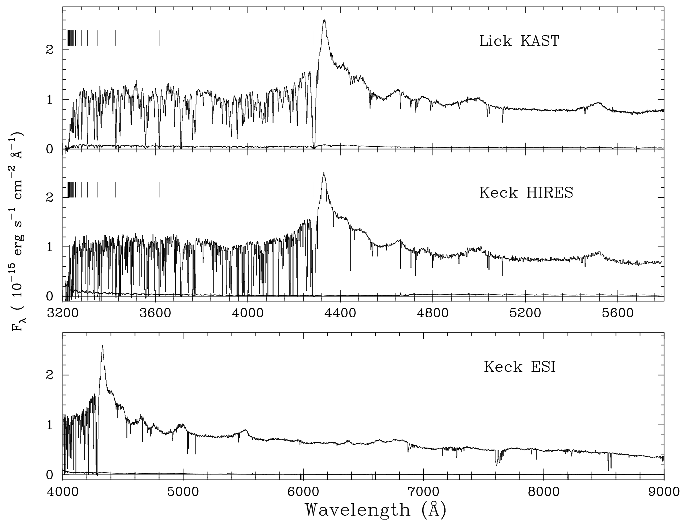
$$\frac{1}{\lambda_{n,m}} = R_H \left(\frac{1}{m} - \frac{1}{n} \right) \quad (10.100)$$

with with Rydberg constant

$$R_H = \frac{m_e m_p}{m_e + m_p} \frac{e^4}{8\pi\epsilon_0^2 h^3} \quad (10.101)$$

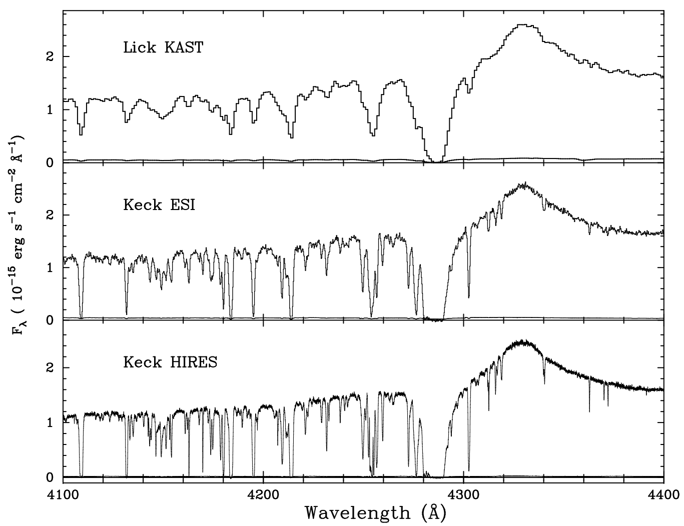
(QSO 1937−1009; top: 3 m Lick, bottom: Keck; Burles, Nollett & Turner, 1999, Fig. 2)

Deuterium, II



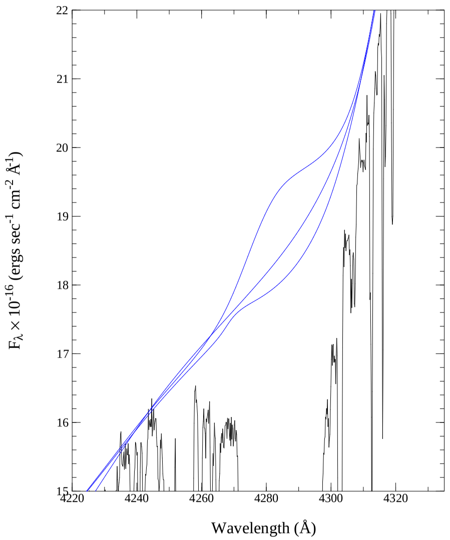
(Kirkman et al., 2003, Fig. 1): Lyman forest against three QSOs

Deuterium, III



(Kirkman et al., 2003, Fig. 2): use absorption close to 4285 Å to measure D/H

Deuterium, IV



To measure abundances, measure column from the optical depth:

$$\tau(\lambda) = n\sigma(\lambda)\ell = N\sigma(\lambda) \quad (10.102)$$

where σ: absorption cross section of line, N: column density. This can be measured from

$$I_{\text{obs}}(\lambda) = I_{\text{cont}}(\lambda)\mathrm{e}^{-\tau(\lambda)} \quad (10.103)$$

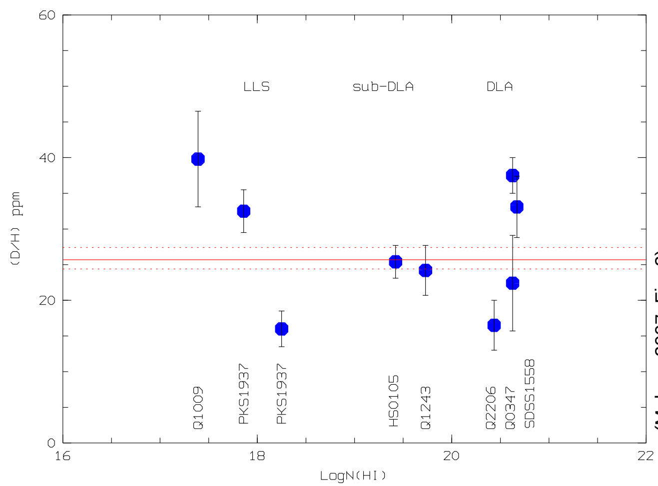
$\Longrightarrow$ Need to know the continuum, I_{cont}
Very difficult to do in Lyα forest (see Figure)

Currently best result for D/H (Kirkman et al., 2003):

$$\text{D/H} = 2.78^{+0.44}_{-0.38} \times 10^{-5}$$

Corresponding to $\eta = 5.9 \pm 0.5 \times 10^{-10}$ or $\Omega_\text{B}h^2 = 0.0214$ ($\pm 9.3\%$).

WMAP BBN and D

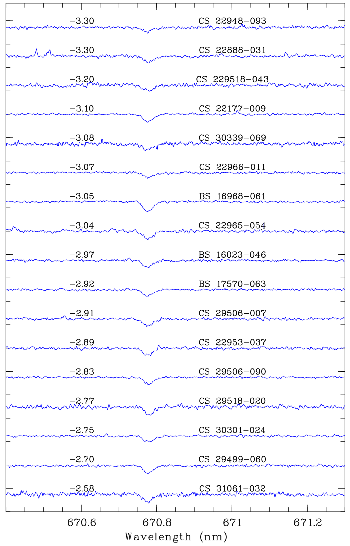


(Molaro, 2007, Fig. 2)

Measured deuterium abundances agree with WMAP predictions

Although there are issues with Milky Way deuterium abundances. . .

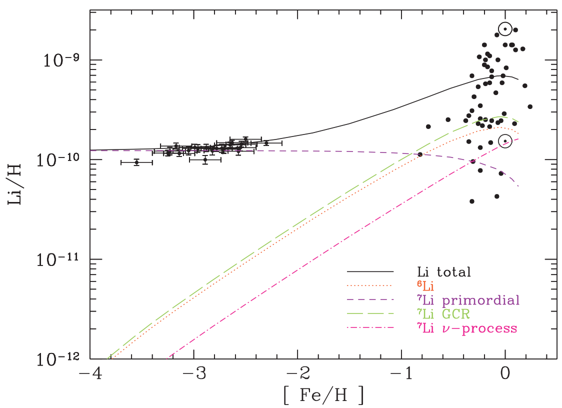
Lithium, I



Lithium lines (Li doublet at 6707 Å) are visible in some stars
$\Longrightarrow$ allow measurement of Li abundance

Li line as a function of [Fe/H]
(Bonifacio et al., 2007, Fig. 1)

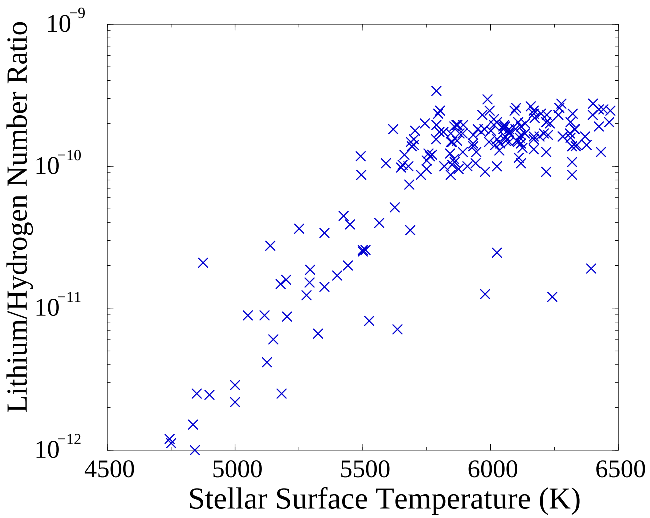
Lithium, II



Olive (2005, astro-ph/0503065, Fig. 21)

To measure primordial Li abundance, one needs to go outside of the Galaxy (i.e., into a low metallicity environment), since inside the Galaxy, Galactic Cosmic Rays produce Li through spallation

Lithium, III



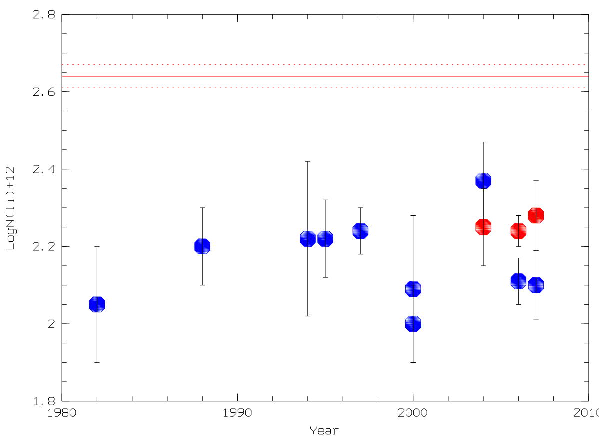
Spite & Spite (1982): Old halo stars with very low [Fe/H]) show primordial Lithium abundance, $^7\mathrm{Li}/\mathrm{H} = 1.6 \times 10^{-10}$

"Spite plateau"

Lower temperature stars: outer convection zone $\Longrightarrow$ Li burning destroys Li.

(Burles, Nollett & Turner, 1999, Fig. 5)

WMAP BBN and Li

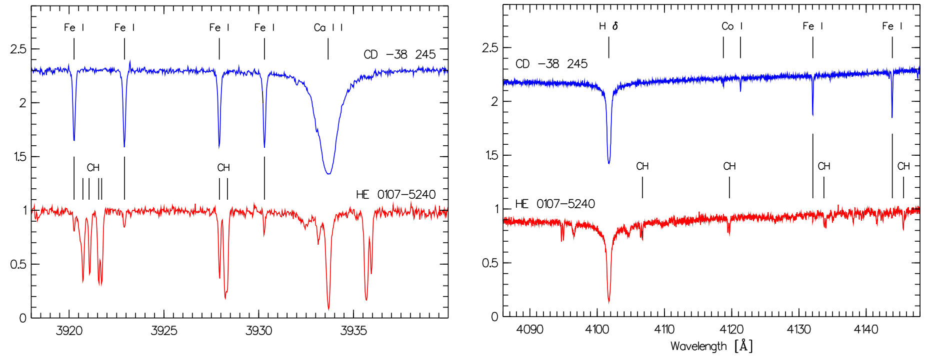


(Molaro, 2007, Fig. 3)

Lithium has a big problem!

Temperature sensitivity might have been underestimated, also rotational mixing, diffusion, and differences between 1D- and 3D-radiative transfer in stellar atmosphere models might play a role. However, no convincing solution has been proposed as of today.

Outlook: Population III

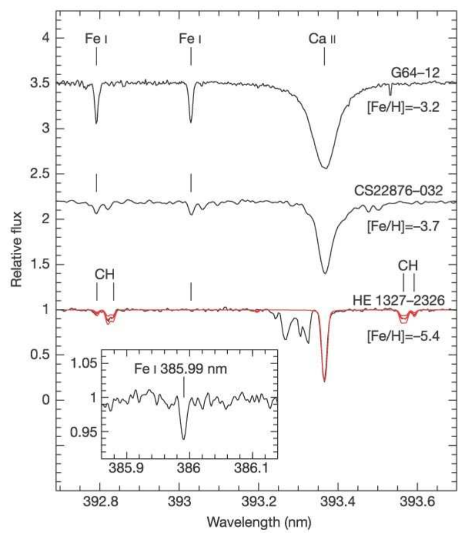


(HE0107−5240, metallicity 1/200000 solar; after Christlieb et al., 2002, Fig. 1)

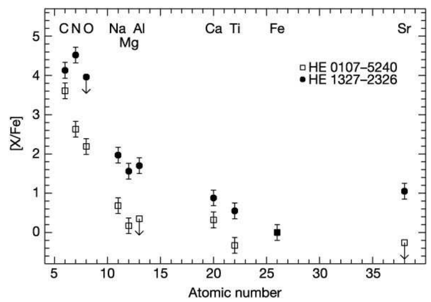
Earliest stars should only have H, He, i.e., $Z = 0 \Longrightarrow$ detection of such stars would enable the *direct* measure of primordial abundances.

"population III star", formed either from primordial gas cloud (and got some elements later through accretion from ISM), or from debris from type II SN explosion.

Outlook: Population III



(Frebel et al., 2005, Fig. 1)



(Frebel et al., 2005, Fig. 2)

Lowest metallicity known: HE1327−2326, with Fe-abundance of 1/250000 solar

Summary

Summary: History of the universe after its first 0.01 s (after Islam, 1992, Ch. 7, see also Weinberg, The first three minutes).

$t = 0.01$ **s** $T = 10^{11}$ **K** $\rho \sim 4 \times 10^{11}$ **g cm**$^{-3}$

Main constituents: γ, ν, $\bar{\nu}$, e$^-$-e$^+$ pairs.

No nuclei (instable). n and p in thermal balance.

$t = 0.1$ **s** $T = 3 \times 10^{10}$ **K** $\rho \sim 3 \times 10^{7}$ **g cm**$^{-3}$

Main constituents: γ, ν, $\bar{\nu}$, e$^-$-e$^+$ pairs. No nuclei.

$\mathrm{n} + \nu \leftrightarrow \mathrm{p} + \mathrm{e}^-$: mass difference becomes important, 40% n, 60% p (by mass).

Summary

$t = 1.1$ **s** $T = 10^{10}$ **K** $\rho \sim 10^{5}$ **g cm**$^{-3}$

Neutrinos decouple, e$^-$-e$^+$ pairs start to annihilate. No nuclei.

25% n, 75% p

$t = 13$ **s** $T = 3 \times 10^{9}$ **K** $\rho \sim 10^{5}$ **g cm**$^{-3}$

Reheating of photons, pairs annihilate, ν fully decoupled, deuterium still cannot form.

17% n, 83% p

$t = 3$ **min** $T = 10^{9}$ **K** $\rho \sim 10^{5}$ **g cm**$^{-3}$

Pairs are gone, neutron decay becomes important, start of nucleosynthesis

14% n, 86% p

Summary

$t = 35$ **min** $T = 3 \times 10^{8}$ **K** $\rho \sim 0.1$ **g cm**$^{-3}$

game over

Next important event: $t \sim 300000$ years: Interaction CMB/matter stops ("last scattering", recombination).

Before we look at this, we look at
the first 0.01 s: the very early universe

Abramowitz, M., & Stegun, I. A., 1964, Handbook of Mathematical Functions, (Washington: U.S. Government Printing Office), (9th reprint, Mineola: Dover, 1972)

Bonifacio, P., et al., 2007, A&A, 462, 851

Burles, S., Nollett, K. M., & Turner, M. S., 1999, Big-Bang Nucleosynthesis: Linking Inner Space and Outer Space, APS Centennial Exhibit, astro-ph/9903300

Christlieb, N., et al., 2002, Nature, 419, 904

Frebel, A., et al., 2005, Nature, 434, 871

Gradstein, I. S., & Ryshik, I. M., 1981, Tables of Series, Products, and Integrals, Vol. 1, (Thun, Frankfurt/M.: Harri Deutsch)

Islam, J. N., 1992, An Introduction to Mathematical Cosmology, Cambridge Univ. Press)

Kirkman, D., Tytler, D., Suzuki, N., O'Meara, J. M., & Lubin, D., 2003, Astrophys. J., Suppl. Ser., 149, 1

Kneller, J. P., & Steigman, G., 2004, New J. Phys., 6, 117

Kolb, E. W., & Turner, M. S., 1990, The Early Universe, Frontiers in Physics 69, (Reading, Mass.: Addison-Wesley)

Molaro, P., 2007, in Pathways Through an Eclectic Universe, ed. J. Knapen, T. Mahoney, A. Vazdekis, in press (arXiv:0708.3922)

Olive, K. A., 1999, in Advanced School on Cosmology and Particle Physics, in press (astro-ph/9901231)

Peacock, J. A., 1999, Cosmological Physics, (Cambridge: Cambridge Univ. Press)

Penzias, A. A., & Wilson, R. W., 1965, ApJ, 142, 419

Smoot, G. F., 1997, in Strasbourg NATO school on the CMB, Kluwer), astro-ph/9705101

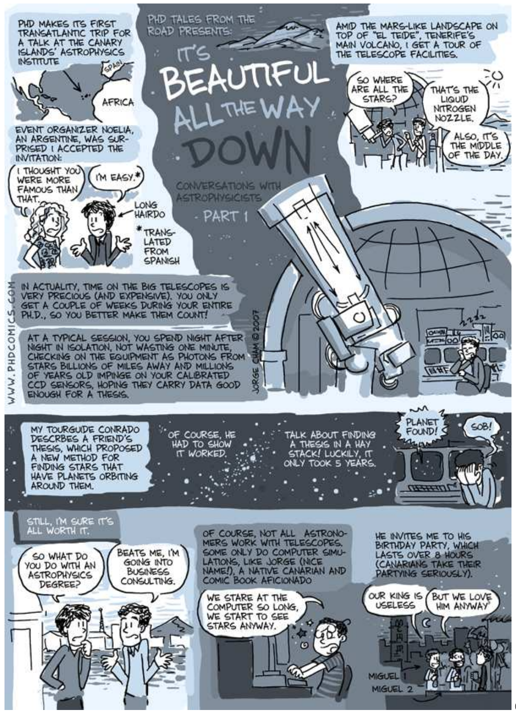
Spergel, D. N., et al., 2007, Astrophys. J., Suppl. Ser., 170, 377

Spite, F., & Spite, M., 1982, A&A, 115, 357

Thomas, D., Schramm, D. N., Olive, K. A., & Fields, B. D., 1993, ApJ, 406, 569

Tytler, D., O'Meara, J. M., Suzuki, N., & Lubin, D., 2000, Phys. Scripta, in press (astro-ph/0001318)

Wagoner, R. V., Fowler, W. A., & Hoyle, F., 1967, ApJ, 148, 3


PHD TALES FROM THE ROAD PRESENTS:
IT'S BEAUTIFUL ALL THE WAY DOWN
CONVERSATIONS WITH ASTROPHYSICISTS PART 1
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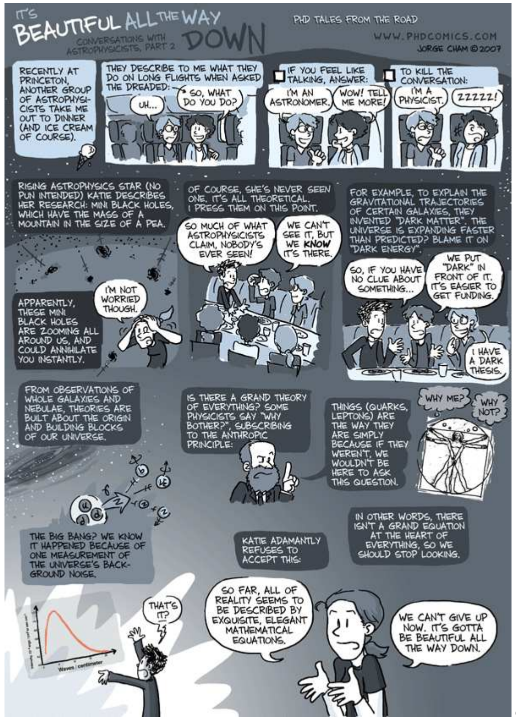
PHD MAKES ITS FIRST TRANSATLANTIC TRIP FOR A TALK AT THE CANARY ISLANDS' ASTROPHYSICS INSTITUTE
AFRICA
AMID THE MARS-LIKE LANDSCAPE ON TOP OF "EL TEIDE", TENERIFE'S MAIN VOLCANO, I GET A TOUR OF THE TELESCOPE FACILITIES.
SO WHERE ARE ALL THE STARS?
THAT'S THE LIQUID NITROGEN NOZZLE.
ALSO, IT'S THE MIDDLE OF THE DAY.
EVENT ORGANIZER NOELIA, AN ARGENTINE, WAS SURPRISED I ACCEPTED THE INVITATION:
I THOUGHT YOU WERE MORE FAMOUS THAN THAT.
I'M EASY.*
LONG HAIRDO
* TRANSLATED FROM SPANISH
IN ACTUALITY, TIME ON THE BIG TELESCOPES IS VERY PRECIOUS (AND EXPENSIVE). YOU ONLY GET A COUPLE OF WEEKS DURING YOUR ENTIRE PH.D., SO YOU BETTER MAKE THEM COUNT!
AT A TYPICAL SESSION, YOU SPEND NIGHT AFTER NIGHT IN ISOLATION, NOT WASTING ONE MINUTE, CHECKING ON THE EQUIPMENT AS PHOTONS FROM STARS BILLIONS OF MILES AWAY AND MILLIONS OF YEARS OLD IMPINGE ON YOUR CALIBRATED CCD SENSORS, HOPING THEY CARRY DATA GOOD ENOUGH FOR A THESIS.
MY TOURGUIDE CONRADO DESCRIBES A FRIEND'S THESIS, WHICH PROPOSED A NEW METHOD FOR FINDING STARS THAT HAVE PLANETS ORBITING AROUND THEM.
OF COURSE, HE HAD TO SHOW IT WORKED.
TALK ABOUT FINDING A THESIS IN A HAY STACK! LUCKILY, IT ONLY TOOK 5 YEARS.
PLANET FOUND!
SOB!
STILL, I'M SURE IT'S ALL WORTH IT.
SO WHAT DO YOU DO WITH AN ASTROPHYSICS DEGREE?
BEATS ME. I'M GOING INTO BUSINESS CONSULTING.
OF COURSE, NOT ALL ASTRONOMERS WORK WITH TELESCOPES. SOME ONLY DO COMPUTER SIMULATIONS, LIKE JORGE (NICE NAME!), A NATIVE CANARIAN AND COMIC BOOK AFICIONADO.
WE STARE AT THE COMPUTER SO LONG, WE START TO SEE STARS ANYWAY.
HE INVITES ME TO HIS BIRTHDAY PARTY, WHICH LASTS OVER 8 HOURS (CANARIANS TAKE THEIR PARTYING SERIOUSLY).
OUR KING IS USELESS
BUT WE LOVE HIM ANYWAY
MIGUEL 1
MIGUEL 2


IT'S BEAUTIFUL ALL THE WAY DOWN
CONVERSATIONS WITH ASTROPHYSICISTS, PART 2
PHD TALES FROM THE ROAD
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RECENTLY AT PRINCETON, ANOTHER GROUP OF ASTROPHYSICISTS TAKE ME OUT TO DINNER (AND ICE CREAM OF COURSE).
THEY DESCRIBE TO ME WHAT THEY DO ON LONG FLIGHTS WHEN ASKED THE DREADED:
SO, WHAT DO YOU DO?
UH...
IF YOU FEEL LIKE TALKING, ANSWER:
I'M AN ASTRONOMER.
WOW! TELL ME MORE!
TO KILL THE CONVERSATION:
I'M A PHYSICIST.
ZZZZZ!
RISING ASTROPHYSICS STAR (NO PUN INTENDED) KATIE DESCRIBES HER RESEARCH: MINI BLACK HOLES, WHICH HAVE THE MASS OF A MOUNTAIN IN THE SIZE OF A PEA.
APPARENTLY, THESE MINI BLACK HOLES ARE ZOOMING ALL AROUND US, AND COULD ANNIHILATE YOU INSTANTLY.
I'M NOT WORRIED THOUGH.
OF COURSE, SHE'S NEVER SEEN ONE. IT'S ALL THEORETICAL. I PRESS THEM ON THIS POINT.
SO MUCH OF WHAT ASTROPHYSICISTS CLAIM, NOBODY'S EVER SEEN!
WE CAN'T SEE IT, BUT WE KNOW IT'S THERE.
FOR EXAMPLE, TO EXPLAIN THE GRAVITATIONAL TRAJECTORIES OF CERTAIN GALAXIES, THEY INVENTED "DARK MATTER". THE UNIVERSE IS EXPANDING FASTER THAN PREDICTED? BLAME IT ON "DARK ENERGY".
SO, IF YOU HAVE NO CLUE ABOUT SOMETHING...
WE PUT "DARK" IN FRONT OF IT. IT'S EASIER TO GET FUNDING.
I HAVE A DARK THESIS.
FROM OBSERVATIONS OF WHOLE GALAXIES AND NEBULAE, THEORIES ARE BUILT ABOUT THE ORIGIN AND BUILDING BLOCKS OF OUR UNIVERSE.
IS THERE A GRAND THEORY OF EVERYTHING? SOME PHYSICISTS SAY "WHY BOTHER?", SUBSCRIBING TO THE ANTHROPIC PRINCIPLE:
THINGS (QUARKS, LEPTONS) ARE THE WAY THEY ARE SIMPLY BECAUSE IF THEY WEREN'T, WE WOULDN'T BE HERE TO ASK THIS QUESTION.
WHY ME?
WHY NOT?
THE BIG BANG? WE KNOW IT HAPPENED BECAUSE OF ONE MEASUREMENT OF THE UNIVERSE'S BACKGROUND NOISE.
KATIE ADAMANTLY REFUSES TO ACCEPT THIS:
IN OTHER WORDS, THERE ISN'T A GRAND EQUATION AT THE HEART OF EVERYTHING, SO WE SHOULD STOP LOOKING.
THAT'S IT?
SO FAR, ALL OF REALITY SEEMS TO BE DESCRIBED BY EXQUISITE, ELEGANT MATHEMATICAL EQUATIONS.
WE CAN'T GIVE UP NOW. IT'S GOTTA BE BEAUTIFUL ALL THE WAY DOWN.