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Lec 9:

Some important moments in the history of the Universe:

As we discussed, according to the "Standard Cosmological Model

the energy budget of the Universe at the present time is:

$\Omega_m \simeq 0.27$ $(\Omega_b \simeq 0.04, \Omega_{CDM} \simeq 0.23)$

$\Omega_\Lambda \simeq 0.73$ ($w = -1$ is consistent with the data)

Radiation makes a negligible contribution $\Omega_{rad} \simeq 5\times10^{-5}$ at this time.

As for dark energy, we consider a cosmological constant that is consistent with the data. Note that:

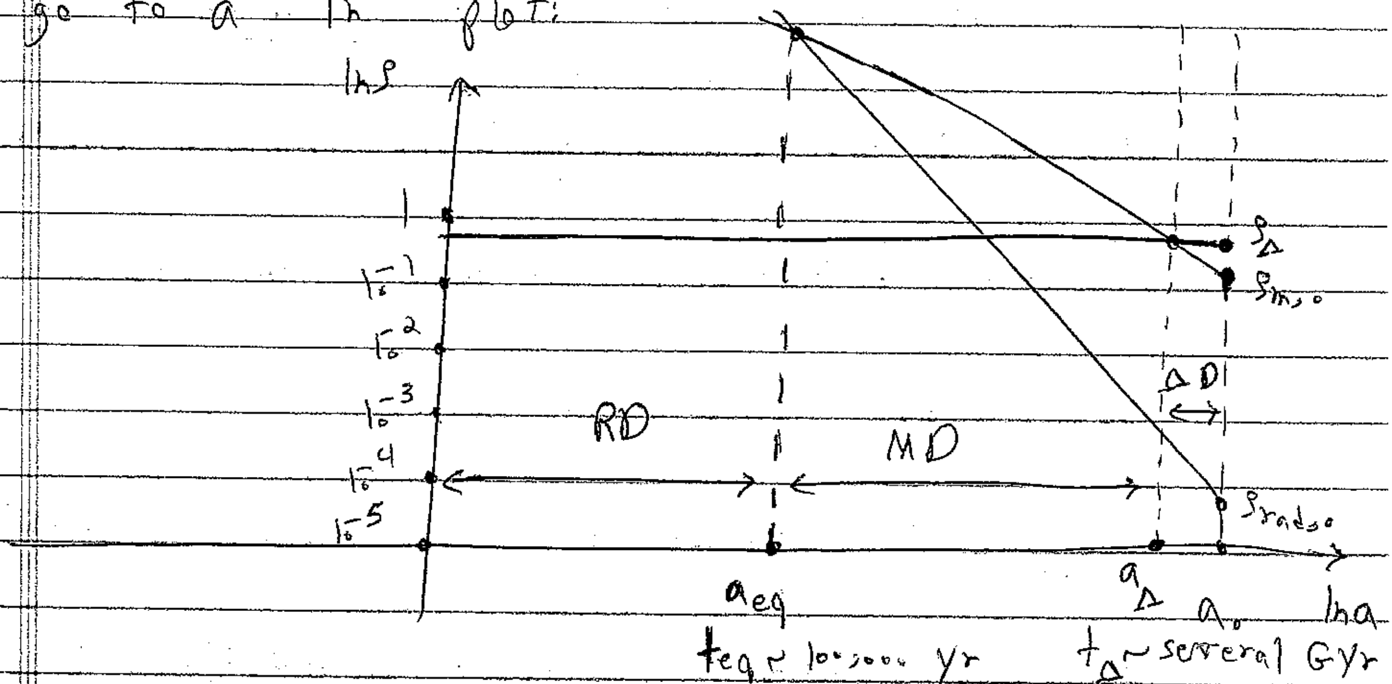
$\rho_m \propto a^{-3}$, $\rho_{rad} \propto a^{-4}$, $\rho_\Lambda = \text{Const.}$

This implies that as we go back in time (smaller "a

ρ_m and ρ_{rad} quickly increase, while ρ_Λ remains Constant.

Lets plot ρ_m, ρ_{rad}, ρ_Λ (all normalized by $\rho_{tot,0}$)

as a function of "a". It is appropriate to go to a "ln" plot:



We see that first ρ_m catches up with ρ_Λ (which is a constant) when $a = a_\Lambda$, and dominates at $a < a_\Lambda$. This happened a few billion years ago. Going further back in time, ρ_{rad} will catch up with ρ_m at a smaller a (and earlier time). This happens at a_{eq}, and ρ_{rad} was the dominant component before then.

Therefore at earlier times ($a < a_{eq}$) the universe was in a radiation dominated (RD) phase. At some point the matter (mostly in the form of dark non-baryonic matter) takes over, after which the univers enters a matter dominated (MD) phase. The energy density in matter is redshifted as a^{-3}, while the energy density in the cosmological constant remains the same (for a general dark energy component the energy density is redshifted more slowly than that of matter). Eventually, the cosmological constant takes over and the universe enters an era of accelerated expansion.

We can find a_{eq} without explicit knowledge of the exact equation of state of dark energy.

At the present time we have:

$\rho_{r} \sim 2 \times 10^{-4} \rho$

And:

$$\rho_m = \rho_{m,0}\left(\frac{a_0}{a}\right)^3 \qquad \rho_{rad} = \rho_{rad,0}\left(\frac{a_0}{a}\right)^4$$

Thus:

$$\rho_m = \rho_{rad} \Rightarrow \frac{a_0}{a_{eq}} = \frac{\rho_{m,0}}{\rho_{rad,0}} \sim 5\times 10^3$$

Recall that:

$$\frac{T_0}{T_{eq}} = \frac{a_{eq}}{a_0} \Rightarrow T_{eq} \sim 5\times 10^3\, T_0$$

$$T_0 = 2.7\,{}^\circ K \sim 3\times 10^{-4}\ eV$$

Here we work in natural units where $\hbar = c = 1$ and $k = 1$ ("k" is the Boltzmann Constant). In this system of units mass, momentum and energy all have the same units, M, While time and length have the same unit $L = M^{-1}$.

We then find:

$$\boxed{T_{eq} \sim 1.5\ eV}$$

To find the time when $\rho_m = \rho_{rad}$ (Called matter radiation equality) we need to know the equation of state of dark energy. It turns out that $t_{eq} \sim 100{,}000$ yr approximately.

The matter-radiation equality is an important moment in the history of the universe. As we will see, the inhomogeneities in dark matter grow fast after matter domination and form potenti wells. Baryonic matter remains coupled to photon for a longer time. Once it decouples from photo as well, then baryons fall into the gravitationa wells and the subsequent growth of their inhomogeneities eventually leads to structure formation.

The decoupling of baryons from photons happen when neutral atoms (mostly Hydrogen) can form. This is called the recombination epoch. Before that energetic photons do not let electrons combine with protons to form atoms. Once the average energy of photons drops below that required to ionize Hydrogen atom then neutral atoms can form.

It turns out that $\underline{T_{rec} \sim 0.3 \text{ eV}}$. This is well below the ground state energy of Hydroge atom $E_0 = -13.6$ eV. The reason being that there are about 10^{10} photons per each baryon in the universe. The photons obey the blackbody spectrum, and hence at $T \sim 0.3$ eV the number of photons with an energy $\sim E_0$ in the Wien tale of the spectrum is large enough to prevent formation of atoms.

Recombination happens few hundred thousand years after matter-radiation equality: $t_{rec} \sim 400{,}000$ yr

After this, photons can freely stream without scattering off free electrons. Actually, this is the epoch we can probe via CMB. More detailed discussion on this will come later.

Another important moment is the time when weak interactions freeze out. Until then the ratio of the number of neutrons to protons was in therm equilibrium. After that this ratio cannot keep its equilibrium value. Neutrons and protons mostly form Hydrogen and Helium (^4He), whose abundance depends on the ratio of the number of neutrons to protons at the weak freeze out. The weak interactions freeze out at $t \sim 1$ sec.

This is the epoch we can probe through big-bang nucleosynthesis (BBN), as we will see later. This is also the earliest time we can directly probe by experiment. The agreement between theory and observation indicates that the universe was a thermal bath of particles (kinematically accessible to the bath) as early as one second when the temperature was $T \sim 1 \text{MeV}$.

There is no direct evidence that the universe was in a thermal state before one second. The next probe can come from dark matter. If we detect dark matter and measure its interaction, then we may have a probe to the time the universe was $\sim 10^{-7}$ sec old.

A remarkable success of the big-bang cosmology is the concordance between the two probes to the early universe, namely CMB ($t_{rec} \sim 400{,}000$ yr) and BBN ($t \sim 1$ sec). They both point to a ratio of baryons to photons that is a few times 10^{-10}. We will discuss this in the content of CMB and BBN in depth.