The early universe

recall the process of recombination that occurred about 400,000 yrs after the big bang & led to the universe becoming transparent to CMB photons

can write recombination as:

$$p^+ + e^- \longrightarrow H^0 + h\nu$$

proton, electron, neutral hydrogen, photon (= energy released by recombination)

comes from both the binding energy of the H^0 (i.e. the e^- goes into the potential well of the p^+, which is $\Delta E = 13.6$ eV deep) Plus the kinetic energy of the p^+ & e^-

* this reaction is exothermic

but it can run in reverse (endothermically) as long as the typical photon has enough energy (13.6 eV) to break apart the H^0 atom

$$p^+ + e^- \rightleftharpoons H^0 + h\nu$$

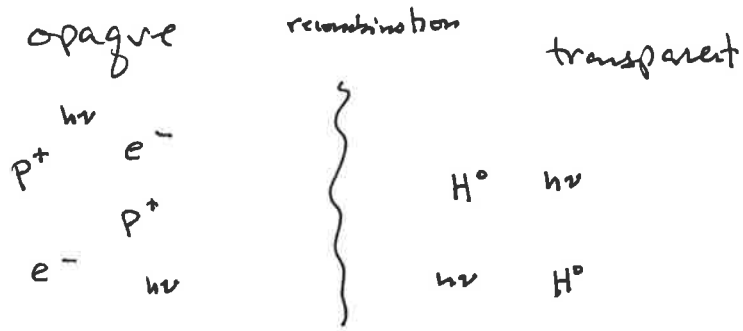
This reaction runs both ways BUT as the universe cools & expands it reaches a temperature where $h\nu$ isn't any longer high enough to drive the endothermic reaction, it then only runs in one direction & lots of H^0 is made while p^+ & e^- disappear. The H^0 "freezes out".

Note: $T_{CMB} = T_{CMB,0}\, a^{-1}$ tells us how big a was when this freeze out occurred & if we have a model of $a(t)$ then we can know the time too

Note also that the redshift, z, corresponding to any scale factor is easily computed from $1 + z = 1/a$

← redshift, temperature

time, scale factor →



"freeze out" of hydrogen

Analogous situation w/ nuclear reactions (note: $p^+ + e^- \to H^0 + h\nu$ is governed by electromagnetism)

e.g.

$$p^+ + n \rightleftharpoons D + 2.2\,\text{MeV}$$

deuterium: isotope of hydrogen

☆ reaction goes both ways early in the Universe, when the temperature is high

but when it "falls" to $T \sim 10^9$ K it only goes to the right (photons no longer have the required 2.2 MeV to break apart a deuterium nucleus)

At that point protons & neutrons get "used up" to make deuterium

but, the amount of deuterium that's made depends on:

1. how fast the Universe is expanding & cooling (reducing the $p^+ + n \rightarrow D$ rate as time goes on) And
2. how much of the D gets used up in other reactions

Fig 24.9 shows the time evolution of the various particles & simple nuclei that are created &/or destroyed in the various nuclear reactions described on p. 566-567

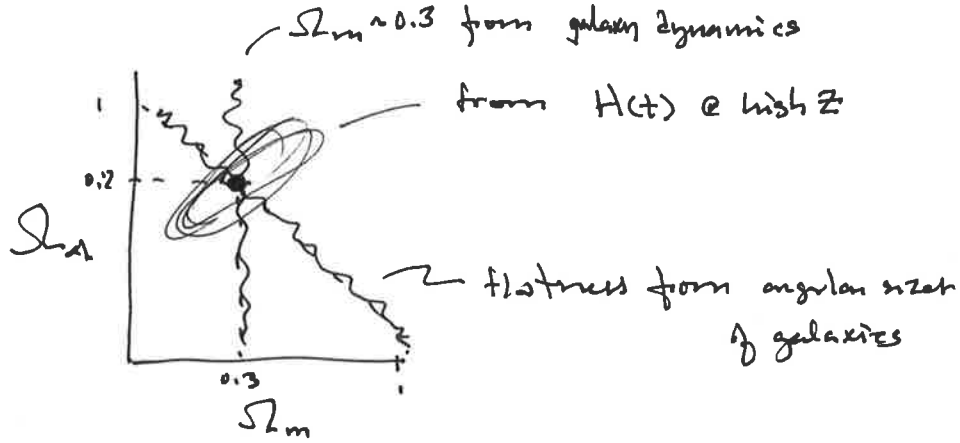
* The fact that the actual, observed abundances of ^4He, ^3He, D, & ^7Li (etc.) agree with the predictions of this model is another very strong, independent piece of evidence for the hot big bang model of cosmology (along w/ the darkness of the night sky, the Hubble law, & the CMB).

Now, the book doesn't state this explicitly but the abundances of these nuclei depends on the baryon density of the universe (as a function of time) $\longrightarrow$ higher density of baryons (p^+ & n) the more D is produced (& eventually He)

* see figure posted on website $\longrightarrow$ observed He, D, Li abundances constrain $\Omega_b \sim 0.04$ (where $h = H_0/110\ km/s/Mpc \approx 0.7$) which is consistent w/ census of starlight + hot gas in galaxy clusters...

...and much less than dynamical determinations of $\Omega_m \sim 0.3$ (confirming that $\Omega_{DM} \sim 0.26$ is non-baryonic)

OK ... can thus summarize the consensus model:



* see photo of black board for more

note: regions of recollapse vs. expansion forever

note also — consensus model has 3 independent pieces of evidence ⟹ even if you take one away you still have $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$

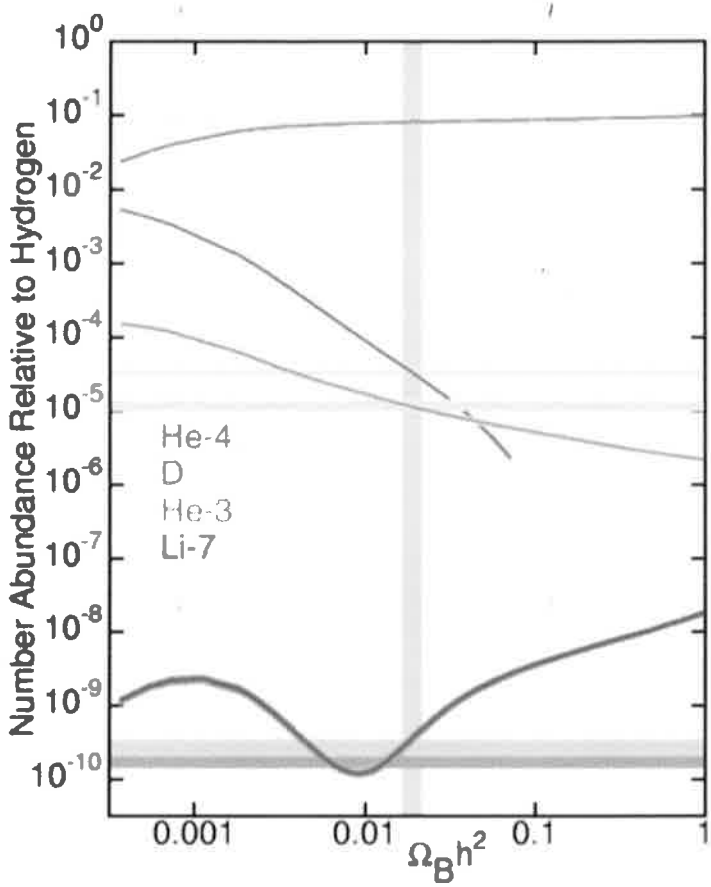
problems (or interesting features) of consensus model:

1. flatness (why is Ω_m so close to 1? it is close now, it was much closer in the past)
2. horizon problem: opposite sides of the sky: CMB has same properties but those 2 spots were never in physical contact w/ each other

also → Sean Carroll's talk — why was early universe in a low entropy state?

proposed solution → INFLATION — brief period of very fast, exponential expansion in the very early universe → because of huge expansion, all of the observable universe was in causal contact; curved space gets very flat (due to stretching)

* What about "fine-tuning"? ⟹ $H_0, \Omega_\Lambda, \Omega_m$ seem designed to give the universe complexity



proportional to the density of baryons

* horizontal lines are observed values of each element