7. History of the Universe

Reading: We're now going to start covering topics in a way that is out of sync with the textbook. There is no one section/chapter of the textbook that corresponds specifically to this section of the course, though much of it is covered somewhere in the book.

I recommend taking advantage of spring break to read chapter 9, on big bang nucleosynthesis, which we will cover next week, and then read chapter 8 through section 8.3. Also, now that we have had several discussions of dark energy and cosmic acceleration, you might want to re-read section 4.5, "Learning to Love Lambda," which you now have more context for.

Age vs. Temperature

At redshift z, the temperature of the photon background is

$$T = 2.73 \times (1+z)\ \mathrm{K}, \qquad kT = 2.39 \times 10^{-4} \times (1+z)\ \mathrm{eV}.$$

Before $z = z_{\mathrm{eq}} \sim 10^4$, the dominant form of energy in the universe was radiation: photons and neutrinos.

Curvature was negligible, so the Friedmann equation can be used to relate the Hubble parameter to the radiation temperature

$$H^2 = \frac{8\pi G}{3}\frac{\epsilon(T)}{c^2}, \qquad \epsilon(T) = a_{\mathrm{SB}} T^4 \times 1.68.$$

The extra 0.68 comes from the neutrino contribution. The T in this equation is actually the photon temperature; the neutrino temperature is somewhat lower.

In a radiation-dominated universe, $t = 1/(2H) \propto 1/T^2$. With the appropriate constants

$$T(t) \approx 10^{10}\mathrm{K} \left(\frac{t}{1\mathrm{s}}\right)^{-1/2}$$
$$kT(t) \approx 1\mathrm{MeV} \left(\frac{t}{1\mathrm{s}}\right)^{-1/2}.$$

Warning: This equation is only valid in the radiation-dominated era.

For example, you can't use it to calculate the age of the universe today.

In this section, we will take a very high-altitude view of the history of the universe.

We'll discuss some of the items on this list in more detail in subsequent sections.

Some major epochs of cosmic history

Planck epoch: $t \approx (\hbar G/c^5)^{1/2} = 5.4 \times 10^{-44}$s.

At or before this time, we expect quantum gravity effects to be important, and calculations based on classical GR to fail.

Inflation

Inflation, a period of extremely rapid, near-exponential expansion during which the universe would have grown by at least a factor e^{57} in size, may be the explanation for the homogeneity and flatness of the universe and for the origin of primordial fluctuations that seeded the growth of galaxies and large scale structure.

Time and energy scale uncertain. Could be as early as the Planck epoch, or could be associated with grand unification, $kT_{\rm GUT} \approx 10^{15}$GeV.

Probably happened before ...

Electroweak symmetry breaking: $kT \sim M_{W,Z} \approx 100$GeV, where $M_{W,Z}$ is the mass of the W and Z bosons that transmit the weak force.

Before this time, the electromagnetic and weak forces were similar in strength and range, because W and Z bosons could be created "freely" from other particles.

Details of this phase transition are poorly understood; we don't know whether it had important effects other than the symmetry breaking itself.

Possibly this is where the matter/anti-matter asymmetry originated.

Quark-gluon plasma: $t \sim 10^{-6}$s, $kT \sim$nucleon binding energy

Before this time, quarks and gluons behave as free particles.

After this time, they appear only bound into hadrons, principally protons and neutrons (the only hadrons with long lifetimes).

Details of this transition are poorly understood.

Big Bang Nucleosynthesis: $kT \sim B_D/20$, $t \sim$2 minutes, where $B_D = 2.2$MeV is the binding energy of a deuterium nucleus.

Origin of the nuclei of ^{4}He, D, ^{3}He, and ^{7}Li.

We'll discuss this epoch (which has several interesting transitions within it) in the next section.

Radiation - Matter Equality: $z_{\rm eq} = \epsilon_{m,0}/\epsilon_{r,0} \approx 3600$, $t \approx 47,000$ years.

At $z \gg z_{\rm eq}$, $a(t) \propto t^{1/2}$.

At $z \ll z_{\rm eq}$, $a(t) \propto t^{2/3}$, until dark energy becomes important at low z.

After $z_{\rm eq}$, gravitational instability can start to grow structure from primordial fluctuations.

Recombination: $kT \approx 13.6\,{\rm eV}/40$, $z \approx 1100$, $t \approx 350,000$ years.

Electrons and protons combine to form neutral hydrogen atoms.

Universe becomes transparent, as the "free electron fog" condenses.

Baryons no longer locked to photons.

The book distinguishes among the epochs of "recombination," "photon decoupling," and "last scattering," but I am going to treat them as synonymous.

Dark Ages

Long period in which there is little or no light from stars and galaxies.

Current best guess is that the first stars in the universe formed around $z \approx 50$.

The end of the "dark ages" is usually defined to be at the epoch of ...

Reionization: $z \sim 10$, $t \sim 0.5\,\mathrm{Gyr}$ (uncertain)

Ionizing photons from stars and quasars reionize the hydrogen atoms outside of galaxies, filling the universe with free electrons again.

Because of the low density, this free electron fog is no longer opaque.

Furthermore, the universe is now mostly transparent to ultraviolet light ($h\nu > 13.6\,\mathrm{eV}$), which would previously have been absorbed by intergalactic hydrogen atoms.

Growth of galaxies and large scale structure

Only very small galaxies had formed by reionization.

In the subsequent 13 billion years, galaxies grew by accreting gas, forming stars, and merging with other galaxies.

Gravity amplified primordial fluctuations (probably created during inflation!) into the clusters and superclusters we observe today.

Cosmic acceleration begins: $z \sim 0.8$, $t \sim 7\,\mathrm{Gyr}$

Observations imply that the universe transitioned from deceleration to acceleration at roughly $z = 0.8$.

The energy densities of matter and dark energy became equal at $z \approx 0.4$.

The future of cosmic expansion depends on the properties of dark energy.