1.11.4. *What are the six numbers that need to be specified to uniquely identify a ΛCDM universe?*

The six numbers are the (current) baryon fraction, the dark matter fraction, the dark energy fraction (ΛCDM assumes that $w = -1$ for dark energy), the curvature fluctuation amplitude Δ_R^2, the scalar spectral index n_s and the reionization optical depth τ. From these values, all others can be derived.

1.11.5. *Why is h often included in cosmological variables?*

h is the dimensionless Hubble parameter, defined as $H_0/(100\ \mathrm{km/(s\ Mpc)})$. It is often included in measurements of cosmological parameters that depend on H_0. Any error in the measurement of the current Hubble parameter can then be removed from the variable in question by including h in the expression (ex. $\Omega_c h^2$ for dark matter density), and relegating errors on H_0 to h.

Current estimates give $h = 0.72$.

1.12. *Question 11*

QUESTION: Outline the history of the Universe. Include the following events: reionization, baryogenesis, formation of the Solar system, nucleosynthesis, star formation, galaxy formation, and recombination.

This short chronology of the universe comes from Wikipedia (2011d), checked with Emberson (2012).

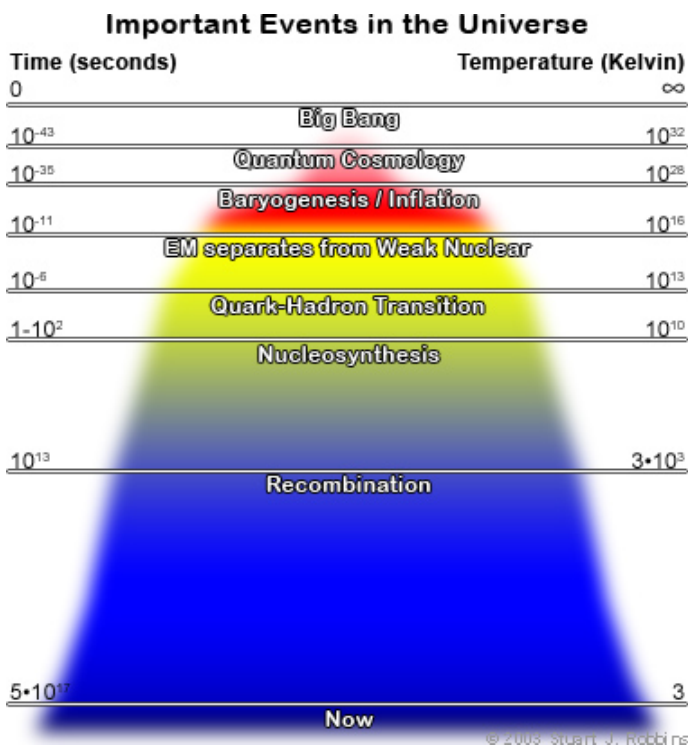

FIG. 17.— The history of the universe, with different cosmological eras, and their corresponding temperature and age ranges, labelled. From Robbins & McDonald (2006).

1. **Planck Epoch** (0 - 10^{-43} s?) - the Planck time is the time it takes light to travel one Planck length, or $t_P = l_P/c = \sqrt{\hbar G/c^5}$, and gives the length of time over which quantum gravity effects are significant. A physical theory unifying gravity and quantum mechanics is needed to describe this era. The four fundamental forces are merged.

2. **Grand Unification Epoch** (10^{-43} - 10^{-36} s?) - gravity separates from electronuclear force, and the universe can now be described by some flavour of grand unified theory (GUT). Separation of the strong nuclear force from the electroweak force at the end of the GUT Epoch produced magnetic monopoles in great quantity.

3. **Inflation** (10^{-36}–10^{-34} s?) - at 10^{-36} (?) seconds (and 10^{15} GeV) cosmological inflation (Sec. 1.16) is triggered. While the true microphysical cause of inflation is not known, Carroll & Ostlie (2006) describes inflation as a bubble of true vacuum (created via quantum fluctuation) surrounded by a false vacuum with a large energy

density (which can be described by a scalar "inflaton field"). For a cosmological constant-like vacuum energy, $w = -1$, and $P = -\rho c^2$; therefore the bubble of true vacuum expanded dramatically. Due to the high energy density of the false vacuum the universe likely cooled to far below 10^{15} GeV by the end of inflation.

Note that the exact timespan over which inflation occured, and how long after the birth of the universe it occured, is not yet well-understood. Times for the Planck and GUT Epochs are those that would have passed assuming no inflation had occurred.

4. **The Electroweak Epoch** (10^{-34} - 10^{-12} s) - the start of inflation coincided with the separation of the strong nuclear and electroweak forces. When inflation ended, the release of potential energy corresponding to the decay of the inflaton field reheated the universe and saturated it with a quark-gluon plasma. At the end of the Electroweak Epoch (10^{-12} seconds and 100 GeV) the weak nuclear force and electromagnetic force decoupled via the Higgs mechanism. Particles gain mass.

5. **Quark Epoch** (10^{-12} - 10^{-6} s) - massive quarks and leptons mingle with gluons in the quark gluon plasma. Temperatures are still too high for hadron formation.

6. **Hadron Epoch** (10^{-6} - 10^{0} s) - the universe cools to the point where quarks binding together into hadrons is energetically favourable. At 1 second (1 MeV) neutrinos decouple from other particles, creating a cosmic neutrino background analagous to the CMB. At the end of this epoch the universe becomes too cold to create hadrons/anti-hadron pairs, and all remaining pairs annihilate, leaving a small hadron excess due to baryogenesis. At some point before this the universe satisfied the Sakharov conditions for baryogenesis, resuting in the universe being dominated by matter over antimatter. This likely occured much earlier in the Electroweak Epoch. Neutron number becomes set at neutrino decoupling.

7. **Lepton Epoch** (10^{0} - 10^{1} s) - hadrons and anti-hadrons annihilate, leaving lepton and anti-leptons. After ~ 10 seconds the universe cools to below the point at which lepton/anti-lepton pairs are created, and the remaining pairs annihilate (except for the small lepton excess due to baryogenesis).

8. **Photon Epoch** (10^{1} - 3.8×10^{5} yr) - photons dominate the universe, interacting with charged particles. At ~ 3 minutes, nucleosythesis (creation of nuclei other than atomic hydrogen) begins, and lasts for ~ 17 minutes, after which the universe becomes too cold for fusion to take place. At 7×10^{4} yrs the matter and photon energy density equalize, and past this time the universe is matter-dominated. Recombination occurs at 3700 K, resulting in the decoupling between matter and photons and the creation of the cosmic optical background (later redshifted into the CMB) at 3000 K (3.8×10^{3} yr).

9. **Dark Epoch** (3.8×10^{5} yrs - 500 Myr) - the universe is largely dark, except for the cosmic background and 21-cm transition of neutral hydrogen.

10. **Reionization Epoch** (500 Myr - $\sim$ 1 Gyr) - the first stars and galaxies form around 500 Myr ($z \sim 10$) after the Big Bang, initiating the reionization of neutral hydrogen across the universe. Reionization begins in pockets, which grow and merge, until the entire universe is reionized at around 1 Gyr ($z \sim 6$). Once the first Pop III stars die, metals are injected into the universe which permit the formation of Pop II stars and planets.

11. **The Modern Universe** ($\sim$ 1 Gyr - 13.7 Gyr) - our own galaxy's thin disk likely formed about 8 Gyr ago. Our Solar System formed at about 4.5 Gyr ago.

1.12.1. *What are the possible fates the universe?*

These scenarios are obviously more speculative.

- **The Big Freeze** - ($> 10^{5}$ Gyr from today) the universe eventually runs out of new material to form stars, and the last stars die out. Black holes eventually evaporate. Some variants of grand unified theories predict eventual proton decay, in which case planets and black dwarfs will also eventually evaporate. The universe eventually turns into a cold bath of particles approaching thermal equilibrium. Under this scenario the universe may eventually approach "Heat Death" at 10^{141} Gyr.

- **The Big Crunch** - (> 100 Gyr from today) the universe recollapses. Unlikely to occur in the ΛCDM concordance model.

- **The Big Rip** - (> 20 Gyr from today) if the EOS of dark energy had $w < -1$, then the dark energy proper density (i.e. measured in kg/m^3) would increase over time, resulting in a runaway expansion.

- **Vacuum Metastability** - (?) if our current universe contains a scalar field that were to suddenly decay in some region of space through quantum tunnelling (much like what occured during inflation), the result would be an inflation-like event where that region would rapidly expand into the rest of space.