Summary of Lecture 25

Key points include:

1. Given that the universe is expanding, if we run the film backward we see that the universe was smaller and denser in the past. Denser also means hotter. We therefore expect (and see!) remnants of earlier eras. For example, there is a primordial glow called the *cosmic microwave background*, or CMB, which comes from when the universe was dense enough to be opaque to light (the universe became transparent at about 380,000 years after the Big Bang).

2. Another signature, from seconds to minutes after the Big Bang, is that the universe was hot and dense enough to produce the lightest elements (hydrogen and helium). This is called *Big Bang nucleosynthesis*, or BBN. The CMB and BBN serve as tests of the hypothesis that the universe was hotter and denser in the past.

3. These are the three key indicators that support the idea of a Big Bang: (a) the expansion of the universe, (b) the primordial glow from the CMB, and (c) Big Bang Nucleosynthesis. All are quantitative and all show that the universe had an origin time, which was about 14 billion years ago (but see below for some apparent problems).

4. As we indicated last time, the current expansion rate, which is measured using the *Hubble constant* (or Hubble parameter) H_0. If something (say, a galaxy) is a distance d from us, then its apparent recession speed is $V = H_0 d$. The best estimate is that $H_0 \approx 70$ km s^{-1} Mpc^{-1}, where Mpc is a megaparsec (i.e., a million parsecs).

5. Given that rate, the fate of the universe depends on how much stuff there is in the universe. Most stuff means larger gravity, and enough stuff could halt the expansion of the universe. This is usually measured in terms of a *critical density* $\rho_{\rm crit}$.

6. Not only is $\rho_{\rm crit}$ important in terms of the fate of the universe; it also tells us the geometry of the universe. If the average density is $\rho = \rho_{\rm crit}$ then on large scales geometry is Euclidean (e.g., the sum of the interior angles of a triangle will be 180°). If $\rho > \rho_{\rm crit}$ then the geometry is like what you'd get on the surface of a sphere (e.g., the sum of the interior angles of a triangle will be $> 180°$), and if $\rho < \rho_{\rm crit}$ then the sum would be $< 180°$. Thus measuring various aspects of the universe can tell us a lot about the fate and geometry of the universe.

7. The terms we give for the geometry are *open* if $\rho < \rho_{\rm crit}$; *flat* if $\rho = \rho_{\rm crit}$; and *closed* if $\rho = \rho_{\rm crit}$. If there were no dark energy, than the geometry would tell us the fate of the universe: an open universe expands forever, a closed universe expands to a maximum size and then recollapses; and a flat universe barely expands forever. Dark energy

complicates that conclusion a bit. But no matter what the geometry, and no matter what the fate, the conclusion of a finite age of the universe, and of an origin very like the Big Bang, remains; open, flat, or closed, there was a beginning.

8. H_0, plus the geometry, can also tell us the age of the universe. Let's define $\Omega \equiv \rho/\rho_{\mathrm{crit}}$, so that $\Omega = 1$ would mean that we're exactly at the critical density. Then with our current best estimate of H_0, and assuming $\Omega = 1$, the universe would be about 9 billion years (thus 9 Gyr) old. But the oldest stars are about 13 Gyr old. Uh-oh...