Summary of Lecture 26

Key points include:

1. Last time we ended on a cliffhanger in the summary: according to our previous calculations, the universe is younger than its oldest stars. That makes no sense. What's happening? We'll keep you in suspense for a few points before we return to this, but you may find that the solution is worse than the problem...
2. Last time we mentioned Big Bang nucleosynthesis, or BBN. From about one second after the Big Bang to a few minutes after the Big Bang, the conditions were right in the universe (hot but not too hot, dense but not too dense) for protons and neutrons to start to form the simplest nuclei. They weren't forming atoms yet because it was too hot for electrons to attach to individual nuclei, but they were forming nuclei.
3. Unlike with nuclear fusion in stars, there was a very limited time available (minutes!) before the universe became cool enough that there was no more fusion. In that time, the universe established the current ratio of hydrogen to helium, with traces of other light elements (e.g., deuterium, which is heavy hydrogen). Helium has continued to be produced (in stars!), but most of the helium we have now was produced in the first few minutes.
4. You only get the right abundances if the total amount of normal stuff (formed from protons, neutrons, and electrons) in the universe is about 4% of the critical density.
5. What??? How can that be? That's a tiny fraction. This means that anything remotely like us, in stars, gas, dust, nebulae, white dwarfs, neutron stars, and the matter that makes black holes from supernovae, is just 4% of the critical density. What's the rest of it?
6. The answer is that *some* of it is thought to be *dark matter*. We learned earlier that when we measure the mass of the Milky Way using gravity we get a number that is larger than what we get when we measure the mass by adding up everything that we can see (e.g., stars and gas). This *could* be because there is something different about gravity itself on those scales, but most people think that this is because there is unseen matter, i.e., dark matter. Dark matter, overall, has about $6\times$ the total amount of stuff as ordinary matter. What could it be? Most people think that it's some new elementary particle. But no particle ever seen, including in the highest-energy colliders, could fit the bill. That's exciting for particle physicists. I do note that it is possible, although not probable, that dark matter is actually black holes formed in the first second (or earlier) after the Big Bang. But there isn't evidence for that either. It's a remarkable mystery.

7. In any event, dark matter is thought to make up most (maybe $\sim 80\%$) of the *ordinarily gravitating* matter in the universe. By that we mean that dark matter attracts (gravitationally) other dark matter and regular matter. That's in contrast to dark energy, which we'll get to in a second...

8. Another amazing conclusion drawn by cosmologists is that in a very early phase of the universe, the universe expanded faster than light(!). This idea is called *inflation*. It doesn't violate Einstein's principle that nothing can move faster than the speed of light; spacetime can expand as it wants, but no matter moves faster than light relative to spacetime. This phase ended at $< 10^{-32}$ seconds after the Big Bang. This can explain a few cosmological puzzles: (a) when all forms of matter and energy (including dark energy) are combined, the universe has an average density very close to the critical density $\rho_{\rm crit}$, which means that it had to be incredibly close to the critical density earlier in the history of the universe, (b) the cosmic microwave background is very, very close to uniform, but without inflation different patches would have evolved differently and we would expect to see much larger variation than we do see.

9. Even dark matter is solid and tangible compared with *dark energy*. In 1998 it was reported (and since confirmed over and over) that instead of the expansion of the universe slowing down with time (which is what you'd expect; it's like a ball that you throw upward slowing down as it rises), over the last several billion years the expansion has been *accelerating*!!! This means that you need some component of the universe which causes *repulsion* instead of attraction (and thus this is *not* ordinarily gravitating mass or energy). People have given this component the name "dark energy". Dark energy is supposed to be everywhere, so the bigger the universe gets, the more important dark energy becomes. In the earlier universe, beyond a redshift of 1 or so, the universe was enough smaller that dark energy was not very important. But now, it's dominating.

10. Einstein actually (reluctantly) modified his theory of General Relativity to include a term that has this effect. But people now think that there is some kind of mysterious energy field that causes repulsion and thus pushes the universe apart. Moreover, this component is *most* of the universe! When you include normal matter, dark matter, and dark energy, the total comes out to very close to the critical density. But 96% of that is in a form that we don't know. That's unsatisfying, but it also means that there is a lot of room for discovery.

11. Given that dark energy is supposed to be everywhere, you might wonder: does this mean that, for example, with time space is expanding within systems such as our Solar System? That is, is the Earth being pushed away from the Sun as the universe expands? The answer is no: on scales small compared with the universe as a whole (the Solar System, a galaxy, even a cluster of galaxies), gravity is strong enough to hold us

together against expansion. But on very large scales (hundreds of megaparsecs), and now (as opposed to the universe past a redshift of 1 or so), dark energy is boss.

12. Remember the age problem we mentioned in the first point above? That turns out to be solved by dark energy. When you include it, along with the rest of the standard model of cosmology, the oldest stars are younger than the universe, as you'd expect.

13. Overall, the standard model of cosmology works really well. There are always mysteries at the frontier, including big ones like "what is dark matter" and "what is dark energy". But if you simply ascribe properties to them, then even without knowing their details we can explain the universe on a large scale.

14. From the philosophical standpoint, it's worthwhile to see how far we've come. Although there are many, many things to explore, we have actually come up with answers to our past and to the universe that were undreamt in 1900. That's some impressive progress.