Lecture 3: Mystery Leftovers (Dark Matter Big Bang Relics)

Definitions

- **In the ΛCDM cosmology, dark matter accounts for 22% of the mass-energy budget of the universe and accounts for 85% of the mass budget. Most of the stuff out there is dark!**

- **There are a few possibilities for dark matter (only one of which is a candidate to make up most of the dark matter)**
  - **Baryonic dark matter.** Baryons are particles made of three quarks, so this family includes protons and neutrons. Baryonic dark matter would be in the form of “normal” stuff, like gas atoms, dim stars, and black holes. But, this can only be a minority of the dark matter.
  - **Non-baryonic dark matter**
    1. **Hot dark matter** (neutrinos are a good candidate). Small-scale structure, including formation of individual galaxies, cannot be explained in an HDM-only model. There can be some HDM, but this cannot be the entire story.
    2. **Cold dark matter.** This is the only candidate which can explain observations. There are several possibilities, which include:
       - Weakly Interacting Massive Particles (WIMPs). This is the one that gets the most attention right now, as we’ll discuss.
       - Heavy sterile neutrinos
       - Axions
       - Kaluza-Klein dark matter

- Neither baryonic nor non-baryonic cold dark matter gives off light. A key difference, however, is that the former still interacts with incoming light rays, while the latter does not interact electromagnetically at all.
Evidence for Dark Matter

- Galactic rotation curves. Without dark matter, galaxies are spinning too fast to hold together.

- Galaxy Clusters
  - Dispersion of galaxy velocities within clusters. The range of galactic velocities is too large without dark matter.
  - Containment of hot gas within galaxies and clusters. X-ray observations show hot gas between the galaxies, but like with the galaxies themselves, this gas requires gravity from dark matter to hold it in place.

- Gravitational lensing. Light bends around massive objects.
  - Strong lensing. We actually observe multiple images of lensed galaxies.
  - Weak lensing. Statistical analysis of galactic orientations shows that lensing is occurring.

- Bullet Cluster (1E 0657-56)
  - In these two colliding galaxy clusters, we can separately examine three components: stars (Hubble telescope), hot gas (Chandra x-ray telescope), and dark matter (weak lensing).
  - In a collision of galaxy clusters, we expect the stars and dark matter components to pass through relatively uninhibited. However, the hot intergalactic gas clouds should interact electromagnetically and slow down. This is precisely what is seen.

- Structure formation. Ripples in the cosmic microwave background, showing the beginning of structure formation, give a measurement of the dark matter content that is consistent with other methods.

- Big Bang Nucleosynthesis, which describes creation of light isotopes by fusion immediately following the big bang, is sensitive only to the baryon density and not to the total matter density. The deduced baryon density agrees with that obtained from the cosmic microwave background and it is far short of the needed total matter density.

Alternatives to Exotic New Particles

- Normal matter distributed inside galaxies that for some reason doesn’t light up. For instance Massively Compact Halo Objects (MACHOs), which could be small black holes, brown dwarfs, neutron stars, or small planets. The possibility that MACHOs could account for all the missing dark matter is ruled out by Big Bang Nucleosynthesis and from lensing searches.

- Galaxy-sized black holes. Ruled out by lensing searches.

- Modified Newtonian Dynamics (MOND). Instead of introducing new particles, this theory proposes that gravity behaves differently on very large length scales,
attempting to account for observations such as the surprising galaxy rotation curves. MOND is not entirely ruled out, but it has a hard time with all the data including Big Bang Nucleosynthesis.

**The Biggest Particle Accelerator Ever Made**
- E = mc² allows us to look for new heavy particles by slamming lighter particles into each other at high energies.
- Accelerator experiments are where many of the particles in the zoo were discovered, and they served as the primary testing ground for development of much of the standard model.
- But, the big bang provided energies which we will never achieve in accelerator experiments. We have a “natural laboratory” for high-energy experiments.
- But to make sense of the results of this laboratory, we need exquisite knowledge of the conditions of the experiments run there—it was 13.7 billion years ago!
- Recent developments in cosmology have made use of this laboratory possible. Already, constraints on Standard Model extensions are being made based on predicted particles which were evidently not produced.

**Supersymmetry and WIMPs**
- Quantum field theory allows for two types of particles: fermions and bosons
  1. **Fermions** have half-integer spin and must each have their own quantum state.
     - Most of the standard-model fundamental particles are fermions, e.g. electrons, quarks, neutrinos.
     - Composite particles made of odd numbers of fermions also are fermions. A proton, made of three quarks, is a fermion.
  2. **Bosons** have integer-spin and can all be crowded into the same quantum state.
     - Photons are bosons.
     - Composite particles made of even numbers of fundamental fermions are bosons. For example, a helium nucleus, made of two protons, is a boson.
- **Supersymmetry is a proposed extension to the standard model**, where every fundamental fermion has a heavier (yet undiscovered) boson partner, and vise versa.
- Supersymmetry is attractive for a few reasons.
  1. It solves the hierarchy problem, which can be expressed two ways:
     a) Why is the weak force $10^{32}$ times stronger than gravity?
b) Why is the Higgs mass so much smaller than the Planck mass? (This question presumes that there is a Higgs particle and it shows up with the properties we expect it to have.)

2. Unification of the strong force with the electroweak force is still not a solved problem, but supersymmetry provides a necessary ingredient that the Standard model has trouble with. In supersymmetry, the coupling constants of the three forces converge at high energies.

- If supersymmetry is correct, we expect to be able to create supersymmetric particles in the next-generation high-energy collider, the Large Hadron Collider (LHC), being built at CERN, near Geneva. Slamming particles together at higher and higher energies, in colliders, is the traditional way of finding new particles.
- However, if supersymmetry is correct, we also expect supersymmetric relics of the big bang
  - In supersymmetric theories, the lightest supersymmetric particle, or LSP, is stable against decay into lighter particles.
  - There should be LSPs left over from the big bang!
  - **Supersymmetry predicts a relic abundance of LSP particles which is in just the right range to account for the dark matter!**
  - This is very compelling! Supersymmetry was proposed to solve problems with the Standard Model, but it also provides natural candidates for a big mystery of the Standard Cosmology. Supersymmetric dark matter might solve two problems at once, which would be nice.
- Here again, advances in cosmology allow us to look for clues in a surprising place.
  - Direct detection of supersymmetric dark matter relics would be a step away from particle physics tradition. Rather than building our own colliders to first detect heavier particles, we would be relying on nature’s accelerator—again one that shut off 13.7 billion years ago.
  - As with the case of neutrino mass limits from Lecture 2, it is a surprising development of modern physics that our detailed understanding of the big bang, an event at the beginning edge of time as we know it, would provide information relevant to solving problems of the Standard Model.
  - We might never detect WIMP dark matter. Supersymmetry might not be the origin of the dark matter or might not be correct. Even within supersymmetry, the LSP might be the gravitino, which interacts only through gravity, not through the weak force. As always in physics, we won’t know until we check!
  - For a while, it will be nice to keep earthbound accelerator experiments complimentary to big-bang accelerator observations. At some point, though, and perhaps soon, we will be unable to keep building larger accelerators.
  - In any case, the next few decades will see astrophysics and high-energy physics working together to refine and challenge the Standard Model.
Next Week – Direct and indirect detection of dark matter