8. Particle Dark Matter

Reading: Chapter 8 (which is about dark matter generally).

A Prelude: Particles and anti-particles in the early universe

For reference, recall our earlier equations

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

If the rates of reactions that exchange energy between particles are fast compared to the expansion rate, the populations should relax to thermal equilibrium.

Consider a particle of mass m_K. If $kT > 2m_K c^2$ and the rate of reactions that can create $K\overline{K}$ pairs from other particles (e.g., photons) are fast compared to the expansion rate, maximizing entropy $\Longrightarrow$an abundance of K and $\overline{K}$ particles roughly equal to the photon abundance (up to statistical weight factors).

More quantitatively, the number density of a coupled species relative to the number density of photons is suppressed by a factor $\exp(-m_K c^2/kT)$.

If the $K\overline{K}$ annihilation rate drops below the expansion rate while $kT > 2m_K c^2$, the particle decouples and redshifts thereafter independent of other species. This happens to neutrinos, and it may happen to other weakly interacting particles.

If the temperature falls below $2m_K c^2$ while the $K\overline{K}$ annihilation rate is high, the particles will annihilate and dump their energy into the background of still-coupled particles. This happens to electrons and positrons.

Evidence for dark matter

There are multiple, strong lines of empirical evidence for the existence of dark matter, including:

- motions of galaxies in clusters
- extended rotation curves of disk galaxies
- gravitational lensing by galaxies and clusters
- temperature and pressure of X-ray emitting gas in groups and clusters

Dark matter resides in extended, roughly spherical halos around galaxies.

Gas dissipates energy and sinks to the center of the halo before forming stars.

Evidently, dark matter does *not* dissipate energy.

Why we think dark matter is non-baryonic

It is hard to package baryons (i.e., objects made of protons, neutrons, and electrons) in a way that is (a) dark and (b) non-dissipative.

(These two generally go together, since matter dissipates energy by emitting electromagnetic radiation.)

The most feasible idea is "Jupiters," self-gravitating balls of hydrogen and helium, but (a) there are no good ideas on how to form them in the enormous numbers required, and (b) gravitational microlensing searches rule them out as the main constituent of the Milky Way dark halo.

There are two other generic reasons for thinking that dark matter consists of a new elementary particle:

1. Big bang nucleosynthesis and CMB observations independently imply $\Omega_{b,0} \approx 0.022h^{-2} \approx 0.05$. But adding up dark matter in halos implies $\Omega_{m,0} \approx 0.2 - 0.25$. There aren't enough baryons to be the dark matter.

2. With the small level of fluctuations observed in the CMB ($\Delta T/T \sim 10^{-5}$), structure cannot grow to the level we see today without non-baryonic dark matter.

The WIMP scenario

In current models of particle physics, it is reasonable for there to be weakly interacting massive particles (WIMPs) that have not yet been discovered.

For example, the theory of supersymmetry predicts a whole family of "superpartners" of standard particles, and the lightest supersymmetric partner (LSP) would be a stable WIMP.

Likely masses for such a stable WIMP are 10 GeV - 1 TeV, with $\sim$ 100 GeV as a "typical value."

The interaction cross-section would be similar in magnitude to other weak interaction cross-sections (e.g., for neutrino scattering).

Revisiting our earlier discussion, the abundance of WIMPs and anti-WIMPS in the early universe would be comparable to that of photons when $kT \gg M_{\rm WIMP}c^2$.

When the temperature drops, the abundance of WIMPs and anti-WIMPS is suppressed by a factor $\sim \exp(-kT/M_{\rm WIMP}c^2)$.

Eventually the WIMP density gets low enough that the typical annihilation time exceeds the age of the universe.

The WIMP abundance "freezes in" at this value, and thereafter WIMPS are just diluted by the expansion of the universe. (This is analogous to the neutron-to-proton ratio "freezing in" at $t \sim$few seconds, instead of staying in thermal equilibrium.)

One can calculate what the relic abundance of WIMPs should be for a typical weak scale mass and cross-section.

Remarkably, it comes out to be roughly what is required to explain the observed density of dark matter.

Detecting WIMPs

Particle astrophysicists are pursuing three routes to try to detect WIMPs.

1. *Indirect detection*

In this scenario, dark matter consists of equal numbers of WIMPs and anti-WIMPs.

In dense regions at the centers of galaxies, the density is high enough to have significant WIMP/anti-WIMP annihilation.

This will typically produce (perhaps as the end of a particle cascade) gamma rays and/or neutrinos, with GeV - TeV energies.

The Fermi gamma-ray satellite was designed in part to look for gamma rays from dark matter annihilation. Ground-based facilities can look for higher energy gamma rays.

These telescopes detect signals, but so far there is nothing unambiguously identifiable as dark matter.

WIMPs annihilating in the center of the sun or the earth could produce a neutrino signal detectable in large neutrino experiments.

2. *Direct detection*

Most WIMPs pass easily through the earth, as do most neutrinos.

But there is a small probability of interacting with a nucleon, producing a recoil.

Direct detection experiments have very sensitive detectors designed to discover these rare events. They are placed deep underground to shield from a false background caused by radioactivity and cosmic rays.

So far, no direct detection experiment has yielded a convincing signal, despite tantalizing hints, but they are getting more sensitive.

3. *Collider production*

The new particle could be produced directly in collider experiments such as the LHC.

On its own, this would not show that the new particle is the dark matter, but it could show that it has the right properties to be dark matter.

There are alternative ideas for particle dark matter.

Some of these alternatives can be tested experimentally, while others would be hard to detect or rule out.

The axion particle, introduced to explain why CP violation in the strong interaction is so weak, is also a good dark matter candidate

If the dark matter consists of axions, then they should be discovered experimentally in the next few years.

Baryon asymmetry

The local universe has baryons but almost no anti-baryons.

This asymmetry is small in the sense that the baryon-to-photon ratio is $n_b/n_\gamma \sim 10^{-9}$. Since the particle density in the relativistic era was $\sim n_\gamma$, *almost* all relativistic baryons were annihilated by anti-baryons.

The baryon asymmetry (and corresponding e^+/e^- asymmetry) may be an initial condition of the universe.

Alternatively, the baryon asymmetry may have arisen after the Big Bang.

A number of specific models of "baryogenesis" have been proposed, none entirely compelling. Some place baryogenesis at the strong-electroweak ("GUT") symmetry breaking, others at electroweak symmetry breaking. Since the level of CP violation observed in the weak interaction is $\sim 10^{-9}$, it is not unreasonable to imagine creating a baryon asymmetry of the observed order.