13. Dark Matter and Structure Formation

Optional reading: Chapter 12. Unfortunately, we will not have time to cover this material at the level of detail it is covered in the book.

We have already covered dark matter in Problem Set 2 and in Section 8 of the course.

Here is some additional perspective, now that we know more about CMB anisotropy and the evolution of the universe.

Structure formation by gravitational instability

At recombination, there were small fluctuations present in the universe, whose imprint we see as CMB anisotropies.

These fluctuations may have originated as quantum fluctuations during inflation.

Overdense regions have stronger gravity, so they expand more slowly than the background universe, increasing their overdensity.

Conversely, underdense regions have weaker gravity, expand faster than the background, and become more underdense.

An overdense region can eventually become dense enough to stop expanding and collapse.

Gravitational instability, acting on small primordial density fluctuations, amplifies them into a network of clumps, filaments, and walls, interleaved with tunnels and bubbles.

Gravitational collapse produces gravitationally bound dark matter halos, with a density profile that is approximately $\rho(r) \propto 1/r^2$.

The "virial radius" of a halo, which roughly separates the region that is in quasi-static equilibrium from the region of continuing infall, is approximately $R_{\rm vir} \sim 200\,{\rm kpc} \times (M_{\rm halo}/10^{12} M_\odot)^{1/3}$.

Galaxies form when gas dissipates energy inside dark matter halos, sinks to the center, and forms stars.

Dissipation of energy + conservation of angular momentum generically leads to disks, while chaotic mergers can lead to ellipticals.

The largest collapsed structures are clusters of galaxies, with $M \sim 10^{15} M_\odot$ and $R_{\rm vir} \sim 2\,{\rm Mpc}$.

Dark matter: capsule history

1930s: Discovery of dark matter from galaxy motions in clusters. Fritz Zwicky.

1970s: Evidence for dark matter in halos around galaxies, from flat rotation curves. Vera Rubin and (many) others.

1980: Inflation hypothesis introduced. Motivates $\Omega_0 = 1$.

Late 1970s and early 1980s: Problems for baryonic dark matter.

- Not enough to explain observed amount of dark matter?
- Hard to keep it non-luminous.
- Models of structure formation with purely baryonic dark matter predict $\sim 10^{-3}$ anisotropies in the CMB, not seen.

Around 1980: New proposal, massive neutrinos are the dark matter. Small mass makes them "hot dark matter," forming structure from the top down, from pancake-like superclusters $\longrightarrow$ galaxies. Yakov Zel'dovich and others.

1982: Another proposal, dark matter is a not-yet-discovered massive particle, "cold dark matter" (CDM). Structure forms from the bottom up, galaxies first. Jim Peebles and others.

Mid-1980s: Computer simulations $\Longrightarrow$ hot dark matter doesn't explain observed galaxy clustering, cold dark matter much more successful. Simon White, Marc Davis, Carlos Frenk, George Efstathiou.

Clusters of galaxies and other probes imply $\Omega_{m,0} \approx 0.2 - 0.4$. Debate over whether $\Omega_0 = 1$ is acceptable. Would require "biased galaxy formation," preferential formation of galaxies in dense regions, so that voids are not as empty as they seem.

1992: First detection of CMB anisotropy by COBE. General agreement with inflation + CDM predictions, but not for $\Omega_{m,0} = 1$.

1998: Direct evidence for cosmic acceleration from Type Ia supernovae.

1999: Direct evidence for a flat universe from CMB balloon experiments.

Today: Excellent agreement of a wide range of data on a cosmological model with primordial fluctuations from inflation, a flat universe, cold dark matter, and dark energy.

But: CDM seems to predict halos that are somewhat too dense in their inner regions. We still don't know what the dark matter particle is, and we don't know what dark energy is.

Martin Schwarzschild's Four Questions, with answers

From Martin Schwarzschild's introduction to a 1985 symposium on dark matter at Princeton.

Do we need it? Yes, many observations point to the existence of dark matter. Modified gravity seems increasingly unlikely as an alternative.

What is it? Probably a weakly interacting particle that is "cold" in the sense that its primordial velocity dispersion was too small to affect structure formation on galactic scales.

Where is it? In extended regions around galaxies and in between the galaxies in groups and clusters.

How much is there? $\Omega_{\mathrm{DM},0} \approx 0.25$, plus baryons with $\Omega_{b,0} \approx 0.05$, most of which are also "dark." The total energy density of the universe of the universe is $\Omega_0 = 1.0 \pm 0.005$, dominated by dark energy.