13. Dark Matter and Structure Formation

Reading: Chapter 7 on dark matter. Chapter 11 on structure formation, but don't sweat the mathematical details; we will not have time to cover this material at the level of detail it is covered in the book.

Look back at Problem Sets 1 and 2 and re-read their solutions.

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.

The first observational evidence for dark matter came from Fritz Zwicky's studies of galaxy motions in the Coma cluster in 1933.

The case became more convincing and more widely accepted with studies of the extended rotation curves of galaxies in the 1970s, by Vera Rubin and others.

The next big U.S. ground-based facility, a survey telescope that will image the entire southern sky about every four nights, is named the Vera Rubin Observatory (VRO) in her honor.

Strong gravitational lensing and weak gravitational lensing added evidence over the 1990s, 2000s.

Success of the ΛCDM model in reproducing CMB anisotropy and low redshift structure is extremely compelling evidence for dark matter.

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* $\rho(r) \propto 1/r^2$, which yields flat rotation curves because $M(r) \propto r$ and $v_c = \sqrt{GM/r}$ =const.

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 diameter of a dark halo is typically $\sim 10\times$ the diameter of the luminous galaxy it contains.

The mass of the dark matter halo is typically $\sim 10\times$ the stellar mass of the galaxy.

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

If structure forms by gravitational instability, then the nature of dark matter is the most important factor governing structure formation.

Why we think dark matter is non-baryonic

1. 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.)

Each of the possibilities — black holes, frozen hydrogen "snowballs" (held together by electrostatic forces), cold or hot gas clouds, Jupiters or very low mass stars (hydrogen and helium held together by gravity) – has serious problems.

2. Gravitational microlensing searches rule out compact massive objects (roughly $10^{-6}M_\odot$ to $10M_\odot$) 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:

3. 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.

4. 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.

With non-baryonic dark matter, the photons and baryons can be distributed fairly smoothly at recombination and fall into dark matter potential wells thereafter.

Neutrinos – hot dark matter

As we discussed when talking about BBN, neutrinos decouple from photons and baryons when $t \sim 1\,{\rm s}$.

The number density of neutrinos and anti-neutrinos (electron, muon, and tau) is similar to that of photons, $n_\nu \sim n_{\bar\nu} \sim 10^9 n_b$.

If the mass of the heaviest neutrino species is $\sim 10\,{\rm eV}$, this would be enough to make up the dark matter.

Because of the low mass, neutrinos would move relativistically in the early universe (until the temperature drops to $kT \sim m_\nu c^2$.

This would erase primordial fluctuations on small scales. First objects to collapse would be "pancakes" (filaments and sheets) 10s of Mpc in length, which would fragment to form galaxies.

This is known as a "top down" or "hot dark matter" scenario for structure formation.

Neutrino dark matter had a burst of popularity around 1980, in part because of an erroneous experimental measurement of neutrino mass.

The theory group of Russian astrophysicist Yakov Zeldovich worked out some of the key ideas of hot dark matter structure formation.

In the mid-1980s, computer simulations by Carlos Frenk, Simon White, Marc Davis, and George Efstathiou showed that "top down" structure formation couldn't make quasars at high redshift ($z \sim 3$) without making excessively large collapsed structures by $z = 0$.

In the late 1990s it became clear that neutrinos have a non-zero rest mass. However, cosmological limits imply that this rest mass is $< 0.5\,\mathrm{eV}$, small enough that they make up only a small fraction of dark matter.

Measuring neutrino mass through its effect on structure formation is a major goal of experiments like DESI and the VRO.

Cold dark matter

In 1982, Jim Peebles – roughly the Western counterpart of Zeldovich – proposed a framework of structure formation with cold dark matter (CDM).

CDM would consist of weakly interacting particles like neutrinos, but moving slowly ("cold") in the early universe because they were much more massive.

Because CDM motions would not erase small scale fluctuations, structure would form from the bottom up: small halos collapse first and merge into bigger structures over time.

This makes it possible to have quasars and galaxies at high redshift and reasonable large scale structure today.

Computer simulations and analytic models with CDM showed much better success than HDM at reproducing observations.

This success leaves (at least) two big questions: what particles make up the CDM, and how much CDM is there?

WIMPs

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 ~ 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).

Recall our equations from BBN:

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

When the temperature of the early universe was $kT \gg M_{\mathrm{WIMP}}c^2$, the abundance of WIMPs and anti-WIMPS in the early universe would be comparable to that of photons.

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

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.

WIMPs are not the only possible form of CDM, but they are still the leading candidate.

How much is there?

Measuring the mass associated with galaxies and galaxy clusters, and adding it all up gives $\Omega_{m,0} \approx 0.2 - 0.4$ (see the solution to Problem Set 1).

We could have $\Omega_{m,0} = 1$ if the large voids seen in the galaxy distribution nonetheless contain a significant amount of dark matter.

This idea is known as "biased galaxy formation" as it implies that galaxies give a biased picture of how matter is distributed in the universe.

Through the 1990s, evidence steadily accumulated against $\Omega_{m,0} = 1$, from galaxy clustering and CMB anisotropy.

However, theoretical arguments, especially inflation, favored $\Omega_0 = 1$ as the "natural" value.

The discovery of cosmic acceleration pointed to a different solution: the universe *is* flat, but $\Omega_{m,0} \approx 0.3$, and the rest of the critical density is made up by a cosmological constant or some other form of dark energy.

The ΛCDM cosmological model assumes a flat universe dominated by a cosmological constant and CDM, also containing baryons, photons, and neutrinos.

We do not have a good explanation for why $\Omega_{m,0} \approx \Omega_{\Lambda,0}$.

Detecting WIMPs

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

1. *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.

The biggest current efforts look for scintillation in tanks of liquid xenon or "listen" for phonons in silicon-germanium crystals, with the signals being produced by nuclei recoiling from a "collision" with a WIMP.

2. *Indirect detection*

In the standard 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.

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.

Other possibilities

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

Axion searches use different techniques from WIMP searches, essentially trying to "tune" a cryogenic microwave cavity so that it matches a frequency at which axions can produce photons.

Dark matter could have more complicated properties than CDM: "warm" DM with velocities that suppress structure on dwarf galaxy scales, self-interacting DM that rearranges itself within halos, even a whole "dark sector" with its own atoms and molecules.

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.