LECTURE 26: DARK MATTER

## 26.1 DARK MATTER IN GALAXY CLUSTERS

Galaxies "orbit" inside a galaxy cluster (much like Population II stars orbit in the Milky Way).

In 1933, Fritz Zwicky measured redshifts of galaxies in the Coma galaxy cluster and found large peculiar velocities (about 1000 km/s).

He argued that the gravity of the observed stars in the cluster was insufficient to hold it together, and that there must therefore be additional gravity from dark matter (Zwicky called it "missing mass").

Zwicky's analysis has been repeated many times for many clusters, with the same result: cluster galaxies have high peculiar velocities, and without dark matter, the clusters would fly apart.

Modern observations provide still more evidence:

- X-ray telescopes reveal hot intergalactic gas. Without the gravitational attraction of dark matter, pressure would expel the gas from the cluster.
- Deep images often reveal giant arcs, the gravitationally lensed images of background galaxies. Dark matter is needed to produce the strong bending of light.

In a typical cluster, $90 - 95\%$ of the mass is dark.

## 26.2 DARK MATTER IN GALAXIES

Most of a typical galaxy's light is in the inner 10 kpc.

If the galaxy's stars provided all of its mass, we would expect the rotation speed to drop outside this radius.

But the rotation speed stays constant $\Longrightarrow$ more mass is needed to hold the galaxy together.

Flat rotation curves imply that spiral galaxies have extended "coronas" or *dark halos* of unseen matter.

The motions of small "satellite galaxies" imply that the dark halos of spirals reach out to 200 kpc or further.

A galaxy's dark halo is much more extended than its light, and it contains most of the galaxy's mass.

There is some evidence that elliptical galaxies have equally large dark halos, but it's harder to tell.

## 26.3 BARYONS

Protons and neutrons are collectively called *baryons.*

Stars, gas clouds, and all "everyday objects" are made of baryons (and electrons, but these don't have much mass).

A key question: is dark matter made of baryons or is it some kind of exotic particle?

## 26.4 BARYONIC DARK MATTER

Several forms have been proposed. The challenge is to package the baryons in a way that keeps them non-luminous.

The most promising idea:

"failed stars" — balls of gas held together by gravity, but not massive enough to start hydrogen fusion in their cores. Sort of like Jupiter.

Other ideas:

diffuse gas clouds — hard to hide from radio telescopes and X-ray satellites.

black holes, neutron stars, white dwarfs — hard to make them without creating too many metals, which would be detected in other stars and in interstellar gas clouds.

"snowballs" of frozen hydrogen — would evaporate in the warm glow of the cosmic microwave background.

There are several large projects underway trying to detect baryonic dark matter. These experiments monitor millions of stars in the Large Magellanic Cloud to look for the effects of gravitational lensing by intervening dark objects in the Milky Way's dark corona.

## 26.5 PARTICLE DARK MATTER

Perhaps the dark matter is some fundamental particle, which influences baryons only via gravity and (maybe) the weak interaction.

Possibility 1:

neutrinos — we know they exist, and the big bang produced lots of them. A very small mass (1/100,000,000 of a proton mass) would be enough.

When the microwave background formed ($t \sim 500,000$ years) they would have been moving close to the speed of light $\longrightarrow$ called "hot" dark matter.

Possibility 2:

a previously undiscovered particle — various new particles are predicted by speculative theories of particle physics.

Most proposed candidates have mass $\sim 1 - 100$ times the proton mass $\longrightarrow$ moving slowly when microwave background formed, "cold" dark matter

There are numerous experiments around the world trying to (1) measure the mass of neutrinos, or (2) discover new particles in accelerators, or (3) detect "cold dark matter" particles as they hit the earth.

### 26.6 DARK MATTER AND STRUCTURE FORMATION

Theories assuming hot or cold dark matter make different predictions for the formation of quasars, galaxies, and galaxy clusters.

Cold dark matter — quasars and galaxies form first, then collect into clusters.

Hot dark matter — clusters form first, then fragment into galaxies and quasars.

Baryonic dark matter — hard to understand how galaxies form at all, though this could just be a problem with our theories of galaxy formation.

### 26.7 HOW MUCH DARK MATTER? WHERE IS IT?

The average mass density of the universe is described by $\Omega$.

Matching the observed helium and deuterium with big bang nucleosynthesis $\Longrightarrow$ baryons contribute at most $\Omega_{\rm baryon} \approx 0.1$.

Adding up the dark matter in galaxy halos gives $\Omega \sim 0.2 - 0.4$.
Implications:

- some dark matter is not baryons (but this conclusion is uncertain)
- the universe is unbound, *if* all dark matter is in galaxy halos

*Cosmic inflation*, a speculative extension of the big bang theory, predicts a balanced ($\Omega = 1$) universe.

There are two ways to reconcile this theory with observations:

- "biased" galaxy formation — if galaxies form only where the density of dark matter is unusually high, cosmic voids could be full of extra dark matter.
- vacuum energy — could make up the difference between $\Omega \sim 0.3$ and $\Omega = 1$.

### 26.8 CHANGE THE THEORY OF GRAVITY?

Perhaps dark matter doesn't exist at all. Instead, our theory of gravity could break down on scales larger than a few kpc.

Until dark matter is detected directly, this possibility cannot be ruled out. **BUT**

No satisfactory alternative theory has been proposed.

It seems unlikely that any alternative would account for
gravitational lensing
the successes of the big bang theory

### 26.9 SUMMARY

Dark matter is matter that we do not see directly (in visible light, radio waves, X-rays, etc.), but which we "detect" indirectly through its gravitational influence on visible matter.

Critical evidence:
flat rotation curves $\longrightarrow$ spiral galaxies have dark halos
galaxy motions, hot gas, gravitational lensing $\longrightarrow$ galaxy clusters are held together by dark matter

$90 - 99\%$ of the mass in the universe is dark matter, and we don't know what it is.

Possibilities are:

baryonic — probably "failed" stars

non-baryonic — "hot" neutrinos (if they have mass)
"cold" particles, previously undiscovered

or some combination of the above

Adding up the mass in halos of galaxies $\Longrightarrow \Omega \sim 0.2 - 0.4$.

A balanced ($\Omega = 1$) universe is possible if

- there is lots of dark matter in voids, far from galaxies
- vacuum energy makes up the difference between $\Omega \sim 0.3$ and $\Omega = 1$

Conceivably, dark matter doesn't exist and our theory of gravity is wrong.

Ongoing searches may reveal the nature of dark matter in the next decade, or failure of these searches may deepen the mystery.