Evidence for Dark Matter

We are now going to move on to another of the most important current mysteries in cosmology: dark matter. To set the stage, we will take a census of the mass in the universe, and show that it has a component that we cannot currently identify or even characterize all that well. Throughout this lecture it will be useful to keep in mind the current critical density that would make the universe flat by itself. That density is $\rho_{\rm crit} \approx 10^{-26}$ kg m^{-3}, which is about $\rho_{\rm crit} \approx 1.4 \times 10^{11}\ M_\odot$ Mpc^{-3}.

Known Mass

Let's start with the easy stuff first: stars. As an especially easy way to estimate the contribution, we note that the number density of galaxies similar to the Milky Way in the local universe is about $n_{MW} \approx 0.003$ Mpc^{-3}. The Milky Way has about $10^{11}\ M_\odot$ in stars, so this would lead to a density parameter of $\rho/\rho_{\rm crit} = \Omega \approx 0.002$. That's pretty far short of the critical density! Of course, not all galaxies are the size of the Milky Way. Adding together the estimated stellar mass from all galaxies leads to a density parameter of maybe $\Omega_{\rm stars} \approx 0.004 - 0.01$. Not much at all.

It turns out, though, that most gas has not formed stars. For example, in galaxy clusters there is several times as much hot gas (at $\sim 10^{7-8}$ K, thus mainly visible in X-rays) as there is stellar material. In the last few years evidence has emerged for a comparable amount of gas between clusters: this is sometimes called WHIM, for warm-hot intergalactic medium. Still, when you add up all the visible stuff, you only get $\Omega \approx 0.04$. This may wound our aesthetic egos, but it isn't necessarily a disaster. Maybe that's just the way it is.

Mass Estimates from Orbits

There is, however, an independent way of estimating masses that does not depend on seeing the stuff. All mass-energy gravitates, so if there are dim but massive things around they can make their presence known. After all, this is the way that we detected the supermassive black hole in the center of the Galaxy.

One approach is to look at stellar orbits at various distances from the centers of galaxies. Of course, we don't wait around the requisite several hundred million years to see the orbit! Instead, observers take spectra of galaxies including our own, determine the line-of-sight speed from Doppler shifts, and then use Kepler's laws to estimate the mass contained inside the orbit of the star.

Starting in the late 1950s, Vera Rubin and others began to find that the rotation curves (i.e., orbital speed versus orbital radius) did *not* behave as expected. A spiral galaxy such as the Milky Way has widely distributed mass, but at the Sun's orbital radius and beyond the number density of stars is much less than it is further in. One therefore does not predict a rotation curve $v \propto r^{-1/2}$ as exists in the Solar System, where there is a single dominant mass. In fact, one expects that the rotation speed should *increase* with increasing radius in the inner ~ 1 kpc. However, the diminishing density at greater radii would be expected to lead to a gradually decreasing orbital speed.

This is not what is seen. Instead, the orbital speed of stars more or less flattens out, to a speed that is therefore called $v_{\rm flat}$ (see Figure 1). This is seen in very large numbers of galaxies. What could be the cause?

One possibility is that there is extra matter we don't see. This is the dark matter hypothesis, and it is held by most of the community. Another possibility is that gravity itself is different than expected on these scales. For example, one suggestion (called MOND, for MOdified Newtonian Dynamics) is that when the normal Newtonian gravitational acceleration drops below a critical value of roughly $a_0 = 10^{-10}$ m s^{-2}, the actual acceleration is larger than Newtonian dynamics would predict. This would mean that for a given acceleration, the required mass is less than would be otherwise needed. This was originally proposed as a phenomenological fit, but there are beginning to be frameworks that might yield this in a relativistic context.

There is, however, additional evidence from larger scales. One can, for example, estimate the mass of a galaxy cluster in three ways. The first two are related: either look at the orbits of galaxies within the cluster and use Kepler's laws, or look at the temperature of the hot gas and assume that it is bound to the cluster. The third involves gravitational lensing, of the weak variety. Basically, by looking at a field of background galaxies through the cluster and noting the image distortions, the cluster total mass and mass distribution can be mapped out. All three methods yield consistent results. At even larger scales, as we will discuss later, the detailed nature of the cosmic microwave background seems to support matter that is not only dark, but "cold" in the sense that it has very little pressure.

Should we therefore believe modified gravity or dark matter? This has been an interesting debate in which aesthetics and, to a degree, politics have played a role. If there is a preferred acceleration scale, this violates Lorentz invariance: some frames become preferred over others. There isn't any particularly natural way this would happen, so most people dismiss this. However, we have seen in the past that aesthetics are not an infallible guide. The politics part comes, in my opinion, from the interesting possibility that some currently unknown elementary particle makes up much of dark matter. This has involved the large and influential particle physics community, and if modified gravity turns out to be the explanation then it would disappoint them.

My current view is that at large scales (cluster and beyond), the specific proposals I've

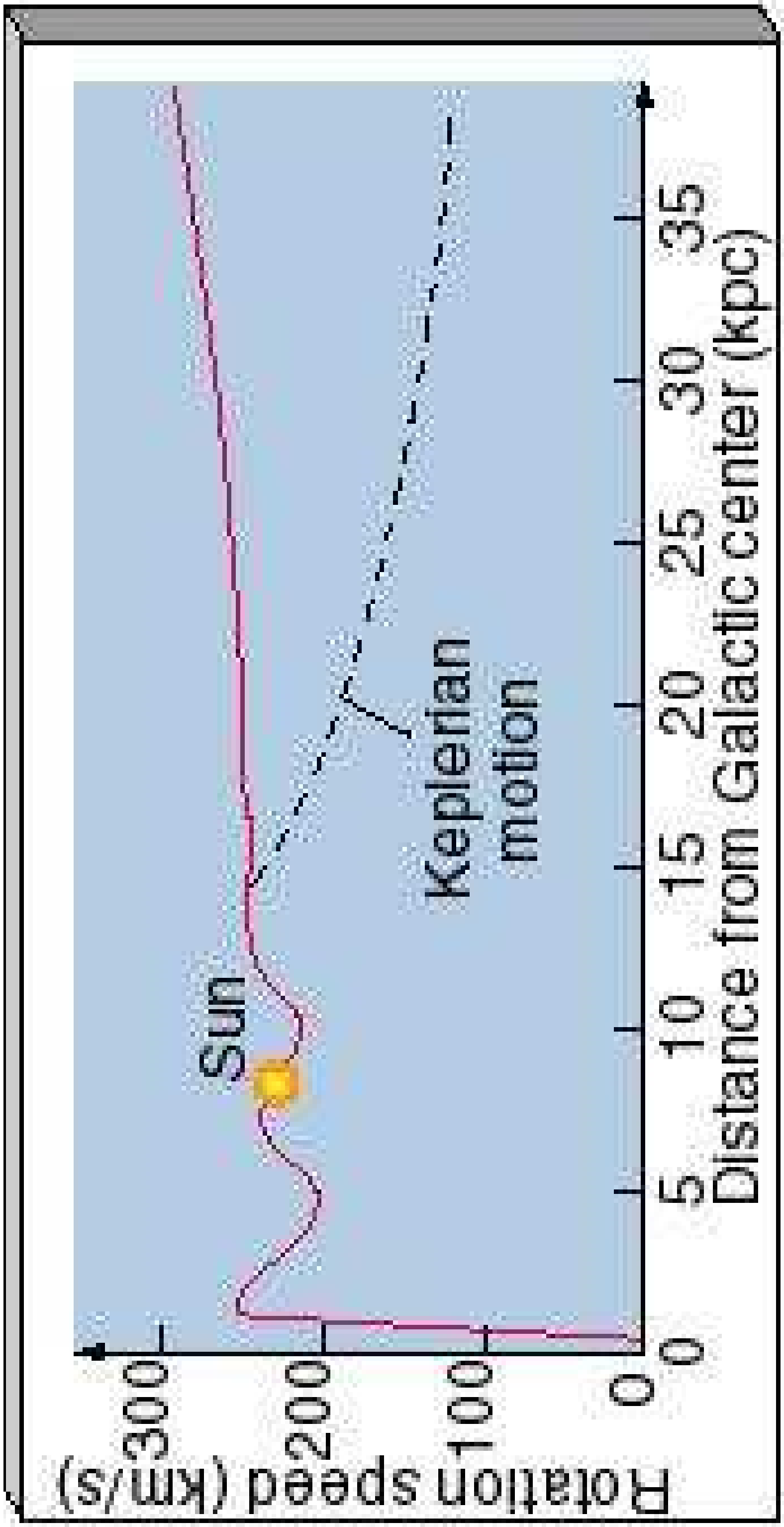

Fig. 1.— Smoothed rotation curve for the Milky Way. The dashed line shows what we would expect if the only gravitating matter were the stars and gas we can see. From http://physics.uoregon.edu/∼courses/BrauImages/Chap23/FG23_019.jpg

seen for modified gravity don't do very well. For example, recently there was a well-publicized analysis of the Bullet Cluster (actually two colliding clusters), that is entirely consistent with pressureless dark matter but not with MOND. On the other hand, at galactic scales MOND does a remarkably good job of matching rotation curves. In contrast, dark matter would have to be distributed in a way that is not easily reconciled with numerical simulations, especially at the cores of low surface brightness galaxies.

If I had to bet, I'd bet on dark matter. There are various processes in the cores of galaxies (e.g., mergers or kicks to black holes) that might account for current discrepancies, whereas the trouble MOND and other ideas have at large scales seem tougher to resolve. The question could be settled if dark matter is actually detected. To determine whether this can happen, though, we need to see what dark matter could be. To square with various observations, the total amount of nonrelativistic matter has to add up to $\Omega_M = 0.27$.

Not Baryons!

A first easy guess is that the stuff is simply hiding in forms that are normal matter, just darker than usual (note that dark matter need not be *absolutely* dark, it just has to have a high mass to light ratio). Examples of known objects with this property include white dwarfs, neutron stars, black holes, and planets. Maybe they're just floating around, and for some reason tend to prefer the outer regions of galaxies.

Remarkably, we can rule out *all* candidates that form from baryons (i.e., protons and neutrons, which carry the mass in normal matter). How? We'll need to wait until the nucleosynthesis lectures to see in detail, but we can give a quick summary here.

The basic idea is that in the first few minutes after the Big Bang, the light nuclei formed. These include hydrogen, deuterium, helium 3 and 4, and trace amounts of lithium and beryllium. The relative amounts of each depend on the total amount of baryons relative to the critical density. As a result, measurements of the primordial abundances of the light nuclei (not an easy thing, but more or less under control) allow us to estimate $\Omega_{\rm baryon}$. The answer is $\Omega_{\rm baryon} \approx 0.04$. If you recall, this is consistent with the total obtained from measurements of stars and gas.

This means, then, that most of the nonrelativistic matter in the universe has to be something that is not baryons! It can't be any stellar remnants, including normal black holes, because the remnants are all made from baryons. It also can't be free-floating planets or Star Trek style "asteroid swarms" or whatever. It really has to be something fundamentally new. The two possibilities have been named MACHOs and WIMPs by an overly hormonal cosmological community. We will consider these in turn.

MAssive Compact Halo Objects

First, the MACHOs. The idea here is that dark matter is arranged in, well, massive compact bundles. The "Halo" portion of the name is because the outer parts of the Galaxy (called the halo) are the bits that require extra mass.

However, we just said that stars, planets, etc. can't be dark matter, so what else is left? Black holes! Er, but didn't I rag on black holes as well because they come from stars, which are made of baryons?

The resolution (maybe) is that there might be a way to produce black holes *before* light element nucleosynthesis, and this would therefore sidestep the constraints we mentioned before. As the universe expanded and became cooler and less dense, it is thought that it underwent a phase transition from free quarks and gluons to the current phase in which quarks and gluons are locked up in hadrons (mainly baryons). During such a density-induced phase transition the matter is extra squishy (more technically, the equation of state is soft). This means that a slightly denser than normal region can collapse more easily than it could normally. This might lead to the formation of black holes which would be a few solar masses. There is, however, some dispute about this because some people think that black holes would be formed across a wide range of masses rather than preferentially at one mass. Because the quark-hadron transition would have taken place some 10^{-5} seconds after the Big Bang, it would be way before nucleosynthesis and thus wouldn't interfere.

This leads to the obvious question: what constraints exist on black holes of a given mass? It turns out that for black holes of less than about 10^{14} kg, Hawking radiation is significant over the age of the universe and there are strong upper limits on Ω_{BH} due to constraints on gamma-ray backgrounds. Between about 10^{-8} and $10\,M_\odot$, microlensing limits Ω_{BH} because of surveys that have been performed on tens of millions of stars in the Galactic bulge and the Magellanic Clouds. The limits are typically $\Omega_{BH} < 0.1$, so these would not be the dominant component. Above about $10^4\,M_\odot$, black holes with $\Omega_{BH} > 0.2$ would have a dynamical impact on galaxies, doing things like destroying globular clusters and fattening spiral disks. This means that the best hope is either between 10^{14-22} kg or around $10 - 10^4\,M_\odot$. So, black holes are possible, but there is no special reason why those mass ranges would be selected.

Weakly Interacting Massive Particles

For these reasons, and also probably due to the interest of particle physicists, most people would point to WIMPs as the best dark matter candidates. We have plenty of particles in the subatomic zoo, so at first it might seem that there are many possibilities.

But there aren't. Suppose for simplicity that we are dealing with just a single type of particle that composes most of dark matter. The first obvious constraint is that the particle should be stable for billions of years. Otherwise, it is the decay products of the particle that have to be dark matter, so we should concentrate on them.

We don't know of many stable particles. Remember that quarks are all bound up in hadrons, so they don't count. Neutrons in free space decay in around 10 minutes. The stable particles that are left are (1) protons, (2) electrons and positrons, (3) neutrinos, (4) photons, and (5) gravitons. Protons are baryons, so they are ruled out. Photons are light, so they are ruled out. Electrons and positrons are also not allowed, because to account for the "collisionless" property we infer for dark matter the particles can't interact electromagnetically (that's why these are *weakly* interacting massive particles). Gravitons travel at the speed of light, so they are relativistic and wouldn't lead to the needed clustering properties of dark matter.

Of currently known particles, this leaves neutrinos. It is still possible that the heaviest of the three generations of neutrinos (the tau neutrino; the others are the electron and muon neutrino) might fit the bill, but a lot of parameter space has been ruled out and most people think this won't work.

If they don't, then we have ruled out all known particles! That's why particle physicists drool at the thought of dark matter: it implies new types of particles. One good category of candidate is the "lightest supersymmetric particle." Supersymmetry is an idea that for every elementary particle that is a fermion (half-spin particles such as electrons, for which only one can occupy a quantum state), there is a supersymmetric partner that is a boson (integral-spin particles such as photons, that like to cluster in a given quantum state), and vice versa. For example, you would have the selectron (a boson) and the photino (a fermion), as well as my favorite, the fermionic counterpart to the W boson: the wino.

None have yet been detected, but they would do a lot of convenient things theoretically. The lightest of these would be stable because it couldn't decay into anything, would be massive, and would interact weakly. It could work. People have designed experiments to detect these because in giant water tanks one would expect an *occasional* interaction, the same way that neutrinos can be detected. There are sometimes reports of possible detections, but so far nothing is compelling. If there is ever such a detection, though, it would provide independent laboratory confirmation of the general idea of dark matter, and would be a triumph of particle astrophysics. In contrast, I cannot think of a lab experiment that would confirm the existence of dark energy. For that, probably the best thing would be an all-encompassing particle and field theory that predicts something with the properties of dark energy. That would be great, but it could take a while!

Intuition Builder

If systems with accelerations $> 10^{-10}$ m s^{-2} are purely Newtonian, do you expect the Solar System to show any non-Newtonian behavior? How about globular clusters, with typical masses $10^5\,M_\odot$ and typical radii 10 pc?