Galaxies

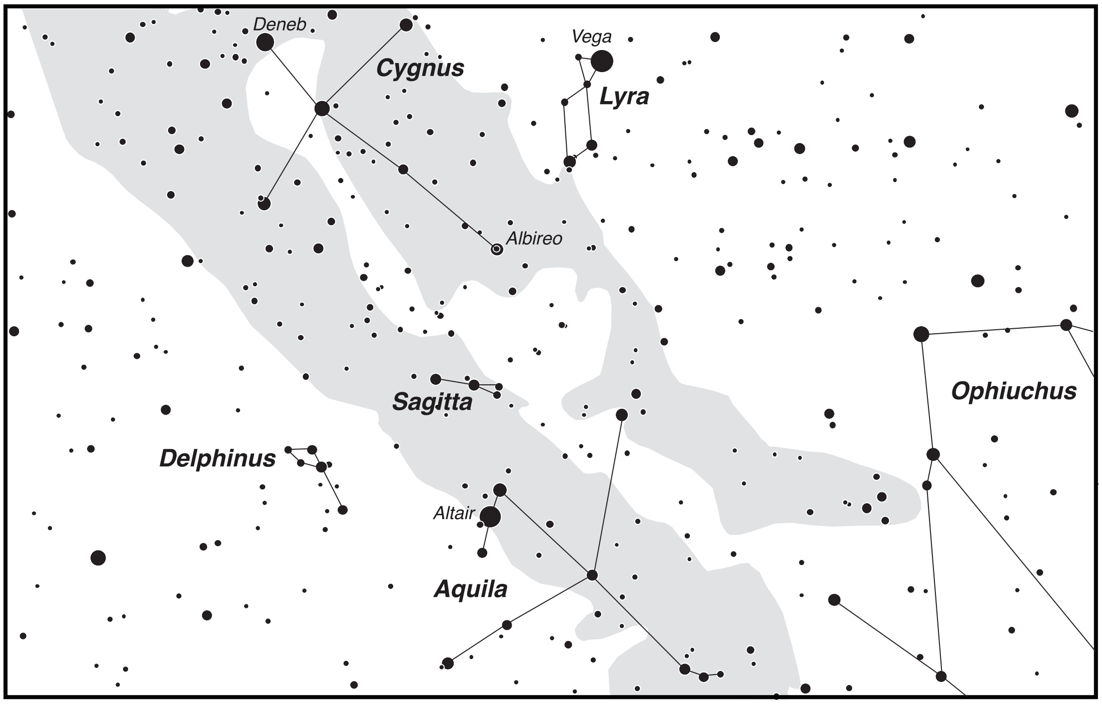
Early History of Galaxies

- The first galaxy to be discovered was our own.

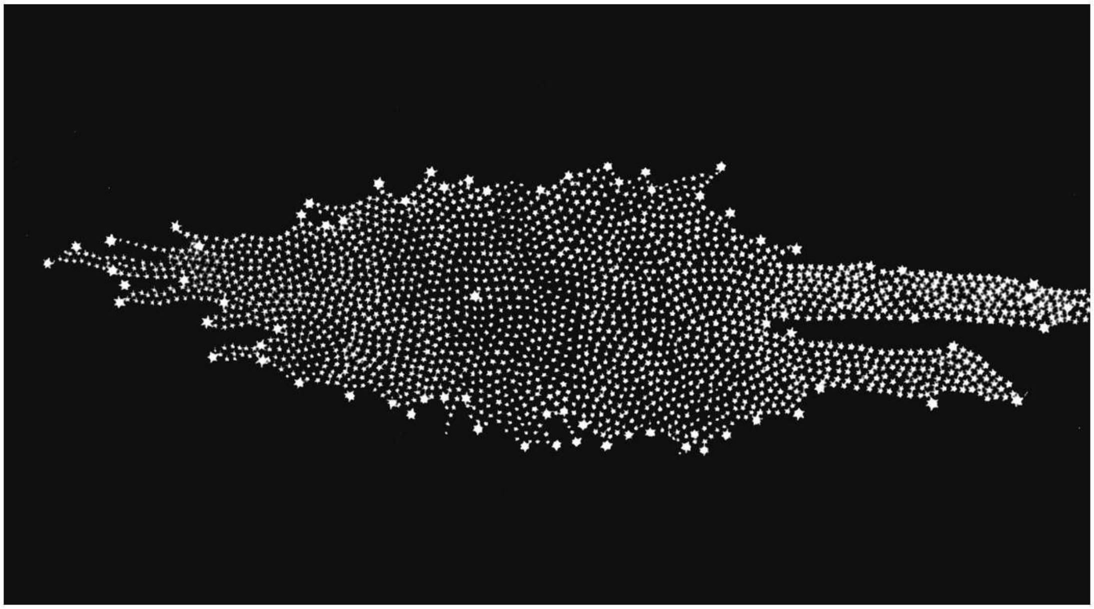
- In era's long before ours, before the glare of modern civilization began to steal the night from the citizens of Earth, it was easy to see on any clear night, arching overhead in the night sky

- To the naked eye, the Milky Way appears as a faint, nebulous glow. It is described often in ancient mythologies. In Greco-Roman mythology, it is the breast milk of the mother goddess, squirted across the sky through some shenanigans of the male elder gods (no surprise there). To the Kaurna Aborigines of southern Australia, the Milky Way is the great river of the skyworld. To the Kung Bushmen of the Kalahari Desert, it is the Backbone of Night, and they believe it holds up the sky.

- The true nature of the Milky Way was not known until the invention of the telescope. Galileo, in one of his many investigations into what the telescope would see when pointed skyward, uncovered a great mystery: the faint glow of the Milky Way was the light of a hundred billion stars, so faint as not to be individually seen except through the telescope.



- The first map of the Milky Way was made by William Herschel in 1785. He used a technique known as *star gauging* – he observed the sky in 600 different directions, and counted the stars he could see with his telescope. He assigned distances to the stars by assuming they all had the same intrinsic luminosity, and assigned a distance based on how bright they appeared.



- Herschel's conclusion: the Sun lies near the center of a large, flattened disk of stars. Note on his map you can see some prominent features of the galaxy, most notably the Great Rift near Cygnus.

The Deep Sky

- The advent of the telescope led to a great reconnaissance of the sky. Early on, the currency of the era was the discovery of comets. It very soon became apparent that there were things to be seen in the telescope that looked like comets, but were not.

- In order to prevent people from being fooled, these *deep sky objects* were cataloged by position, brightness, and appearance. One of the earliest was the catalog of Charles Messier. The Messier Catalog (objects labeled M) is 110 of the brightest objects in the night sky, and are still vigorously observed by amateurs and professionals alike.

- The first great catalog to systematically cover the entire sky was the *New General Catalog* (objects labeled NGC) and its companion *Index Catalog* (objects labeled IC). The NGC consists of 7840 objects, and was compiled by J.L.E. Dryer using observations from William Herschel and John Herschel. Dryer compiled a further list of 5386 objects into the IC.

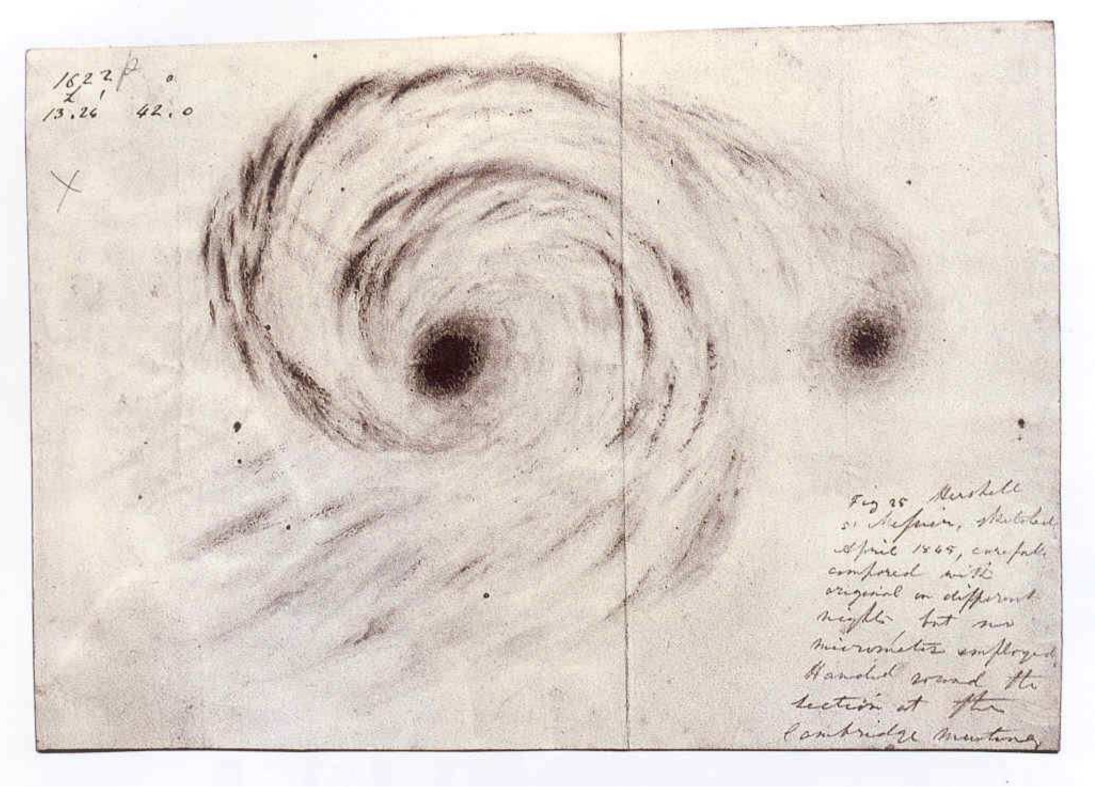
- For many deep sky objects, their nature was clear. The Pleiades (M45) is quite clearly a cluster of stars that looks faintly nebulous to the eye or in poor telescopes. Many other deep sky objects were *always* fuzzy blobs.

- For instance, the first globular cluster discovered was M22 (found in 1665 by Abraham Ihle), but no stars were resolved in *any* globular cluster until Messier observed M4 in 1764 (M4 had been discovered in 1746 as another round blob by Cheseaux).

• Many other deep sky objects were never resolved into individual stars. Most famous among these were objects such as the Lagoon Nebula (M8), the Orion Nebula (M42), and the Andromeda Nebula (M31).

• Much speculation was had about whether or not there were other galaxies like our own, or whether the Milky Way was, in fact, the entire Universe. As early as 1755 Immanuel Kant had speculated, on purely philosophical grounds, that there must indeed be other *island universes* like the Milky Way.

• The question was thrown into harsh relief in 1845 when William Parsons (Lord Rosse) used the 72 inch telescope (the "Leviathan of Parsonstown," the largest telescope of the 19th Century) to observe M51 and detected for the first time *spiral structure.* It would later come to be called the *Whirlpool Nebula.*



• He promptly declared that M51 was an *island universe*, bringing Kant's supposition into the limelight and setting off one of the greatest scientific debates of all time.

The Great Debate

• The argument over the nature of the spiral nebulae rapidly fragmented into two camps — those who believed the Milky Way was the whole Cosmos and everything was embedded within it, and those who believed the spiral nebulae were island universes farther away than had ever been imagined.

- There were arguments and observations on both sides, but little movement toward a consensus. The nature of this scientific conflict has passed into the folklore of astronomy, and has been embodied by a public scientific debate known as the *Shapley-Curtis Debate*, or simply *The Great Debate*.

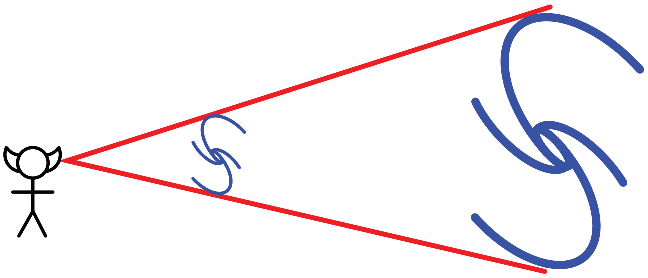
- The debate was held on 26 April 1920 at the Smithsonian Museum of Natural History between Harlow Shapley (the director of the Mount Wilson Observatory, near Los Angeles) and Heber Curtis (the director of the Allegheny Observatory, near Pittsburgh).

- The day was filled with a scientific meeting and presenting of results on both sides of the issue, followed by a public debate in the evening between Curtis and Shapley. The summary was published by the two in 1921 in the Bulletin of the National Research Council.

- Let's show some physical examples of the kind of data that each of these astronomers was appealing to in order to support their (opposing) viewpoints

Shapley: The Milky Way is the Universe ▶ . . . .

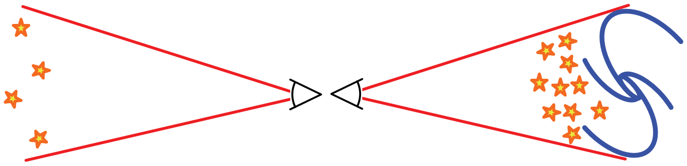
- The Andromeda Nebula subtends a large area on the sky (nearly $190' \times 60'$). If it was indeed an island universe, and it was the size Milky Way, then it would be *enormously far away* — remember, no concrete scale for the Cosmos had been established at this time; distances larger than the size of our galaxy were hard to imagine.



- A Dutch astronomer named Adriaan van Maanen had measured the rotational speed of the Andromeda Nebula. If it was indeed an island universe, and it was far beyond the boundaries of the Milky Way, then van Maanen results would have predicted the stars were rotating faster than the speed of light (even then this was known to be an impossibility).

Curtis: The Spiral Nebulae are Other Galaxies ▶ . . . .

- There was a nice statistical argument regarding the spatial density of novae on the sky. The average number novae observed toward the Andromeda Nebula was much larger than the average number of novae observed on similar sized patches of the sky elsewhere, suggesting the Andromeda Nebula was a galaxy producing as many novae as the Milky Way



- Large recessional velocities (Doppler redshifts) had been measured in spiral nebulae, suggesting they were different from other nebulae (though no one knew why).

Outcome of the Great Debate ▶..

- In the end, the Great Debate did little to change anyone's mind on that spring day in 1920. The simple fact of the matter was, ***we needed better data.***

- This is the nature of science — we all hold our positions until such a time as there is a set of data that everyone agrees upon. In the end, the data would come from a young astronomer at the Mount Wilson Observatory — Edwin Hubble.

The Distance Ladder

- They key to resolving the debate over the nature of the spiral nebulae was figuring out a way to determine the distance to the nebulae.

- As we have encountered before, measuring distances in astronomy is a hard problem. Different methods are described as rungs on a *distance ladder.* The lowest rungs represent the easiest and most reliable ways of measuring distance. Successive rungs bootstrap based on the lower rungs of the ladder.

- The simplest method to measure distance is if an object has a known absolute (intrinsic) brightness. If you can measure the flux F and know the luminosity L then

$$F = \frac{L}{4\pi r^2} \qquad \rightarrow \qquad r = \sqrt{\frac{L}{4\pi F}}$$

- The difficulty with this method? *You have to know the intrinsic luminosity for it to work! That's not always possible!*

- The next easiest and most trusted method is to use *parallax* – the angular shift in position of an object when it is viewed from different locations, such as the opposite sides of the Earth's orbit.

- The angle θ is called the *parallax angle.* If you measure the angle θ using the diameter of the Earth's orbit, then the small angle formula gives the distance d to the object. If $s = 2a_\oplus$, where $a_\oplus$ is the radius of the Earth's orbit, then

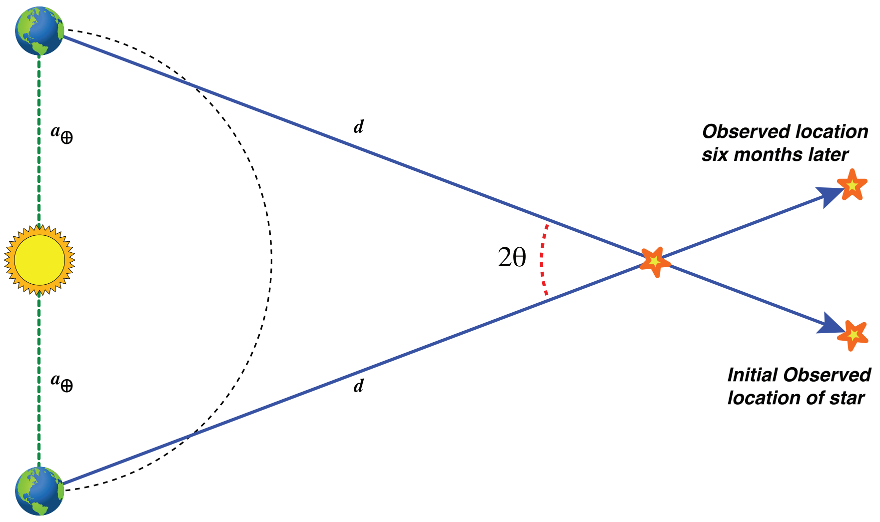
$$s = d\theta \qquad \rightarrow \qquad 2a_\oplus = d \cdot 2\theta \qquad \rightarrow \qquad d = \frac{a_\oplus}{\theta}$$

where θ is measured in radians.

- In practice, the ability to measure small angles (like parallax angles) is limited by the *angular resolution* of a telescope.

- The angular resolution of a telescope is theoretically given by the Rayleigh limit. For a telescope of aperture D observing at wavelength λ the limiting angular resolution θ is

$$\sin\theta = 1.220\frac{\lambda}{D} \qquad \rightarrow \qquad \theta \simeq 1.220\frac{\lambda}{D}$$



- Note that this can be rewritten to give the *linear size formula* by using the small angle approximation: $s = r\theta$. The smallest size s that a telescope can resolve at a distance r is given by

$$s \simeq r \cdot \lambda / D$$

[▶ EX ◀]Angular Resolution of Hubble

The Hubble Space Telescope has a diameter of $D = 2.4$m. If it is observing at optical wavelengths, say $\lambda = 550$ nm, what is the maximum distance d at which it could detect stellar parallax?

The parallax measurement is made across the diameter of the Earth's orbit, so the angular shift θ is

$$\theta = a_\oplus / d$$

Combining this with the Rayleigh limit (neglecting the factor of 1.220)

$$\theta = \frac{a_\oplus}{d} = \frac{\lambda}{D} \qquad \rightarrow \qquad d = \frac{a_\oplus D}{\lambda} = \frac{1.496 \times 10^{11}\text{m} \cdot 2.4\text{m}}{550 \times 10^{-9}\text{m}} = 6.53 \times 10^{17}\text{m} = 69 \text{ lyr}$$

- Using parallax is not going to get us very far out into the Cosmos. We need a better away. As it turns out, we have one. It was discovered in 1912 by a woman named Henrietta Swan Leavitt.

Cepheid Variables

- As of 2005, nearly 40,000 pulsating stars had been catalogued by astronomers. More than 5% of those stars had been discovered by Henrietta Swan Leavitt, while working at the Harvard College Observatory.

- Leavitt was studying 2400 stars in the Small Magellanic Cloud. Since all of them were roughly the same distance away, she knew that the distribution of apparent magnitudes m was really just the distribution of the absolute magnitudes M adjusted for the distance to the SMC.

- She discovered that the the *pulsation period* was related to the *absolute brightness*. The brighter the star, the longer the pulsation period. These stars are called *Cepheid Variables*.

- ***This is one of the most important discoveries ever made in astronomy.*** It means that if you simply measure the period of pulsation of a Cepheid, then you know what its absolute brightness is. If you then measure the apparent brightness with your telescope, *you can determine the distance to the star using the distance modulus formula.*

- The relationship between the period P_d (measured in days) and the absolute magnitude M_v in the V-band is given by the ***period-luminosity relation***

$$M_v = -2.81 \log P_d - 1.43$$

- The first person to make serious use of this relationship was Enjar Hertzsprung (of HR diagram fame), who almost immediately realized the importance of Leavitt's discovery and started using the method to measure distances in the Milky Way.

- In 1924, Edwin Hubble used the 100" Hooker Telescope on Mount Wilson to observe the first Cepheids in the Andromeda Nebula. Hubble's measurement demonstrated conclusively that M31 was *not* part of the Milky Way, and was indeed very far away. He had discovered the ***Andromeda Galaxy***.

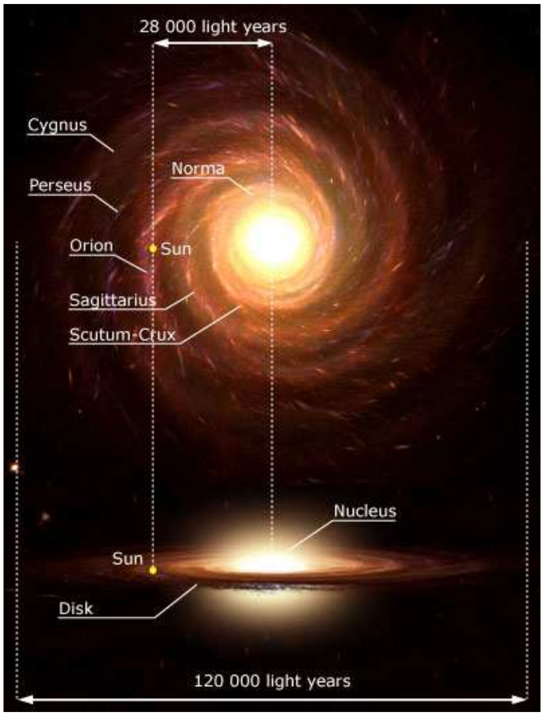
Physical Properties of the Milky Way

- Once you can start making measurements of the Milky Way, you can start ascertaining its properties. Furthermore, the advent of astronomy at different wavelengths has proven invaluable, since it allows us to probe throughout the galaxy, even in the presence of obscuring gas and dust (like the Great Rift).

- The galaxy is comprised of three basic components: the *disk*, the *bulge*, and the *halo*.

- The disk is $\sim 120,000$ lightyears in diameter, and ~ 1000 lightyears thick. The central bulge is $\sim 10,000$ lightyears in diameter. The halo is of unknown size, but at least $300,000$ lightyears in radius.

- The Sun is located about 8 kpc from the cen-



ter of the galaxy, and orbits the galaxy once every 250,000,000 years.

• We can use this as a starting point to estimate the mass of the galaxy, by looking at the Sun's orbit. Using Kepler III:

$$G(M_{gx}+M_\odot)=\frac{4\pi^2}{P_\odot^2}a_\odot^3 \qquad \rightarrow \qquad M_{gx}\gg M_\odot \text{ so} \qquad \rightarrow \qquad M_{gx}\simeq\frac{4\pi^2}{GP_\odot^2}a_\odot^3$$

Inserting the values for the Sun's orbit (converted to SI units):

$$M_{gx}\simeq\frac{4\pi^2\cdot(2.47\times10^{20}\text{ m})^3}{6.67\times10^{-11}\text{ Nm}^2/\text{kg}^2\cdot(7.89\times10^{15}\text{ s})^2}=1.43\times10^{41}\text{ kg}\sim7\times10^{10}M_\odot$$

• So the galaxy has at least the mass of *100 billion suns*. All told, measurements suggest that the total mass is on order of 100 trillion solar masses ($10^{12}M_\odot$).

• In 2005, it was discovered that the Milky Way does not have a spherical bulge, but rather an elongated bar structure in the core. The bar was difficult to observe due to obscuration by dust and gas, but also because we are looking at it at a very shallow angle, only $\sim 30°$ from end on.

Other Galaxies & Galactic Morphology

• We are looking at the Milky Way from *within*; we see the disk edge-on. We can learn about the Milky Way by observing other galaxies, then inferring back to our own.

• How many other galaxies do we have to look at, and where in the Cosmos are they?

• The Hubble Deep Field was an image captured by the HST in 1995. They observed for 10 days, making 342 exposures. All told, 3000 galaxies were found in an area only 2.5 arcminutes across (about the size of Roosevelt's eye, if you hold a dime at arm's length).

• Numbers like this lead to estimates of there being $\sim 10^{11}$ total galaxies in the observable universe. On the largest scales, they are more or less distributed uniformly on the sky. A good number to carry around is that there are $\sim 10^5$ galaxies per square degree on the sky.

• The closest galaxy to us is a small satellite galaxy of the Milky Way known as the Canis Major Dwarf Galaxy, about 25,000 lightyears away, discovered in 2003. Recent analyses have raised a debate as to the existence of this galaxy, positing it might be a warped extension of the Milky Way.

• The farthest galaxy is a record that changes hands often as we probe deeper and deeper into the Cosmos. The current record is held by Abell 1835 IR1916, located 13.23 billion lightyears away.

• If you study enough galaxies, you begin to notice that many galaxies look the same. The taxonomy of galaxies is based on their visual appearance, the *morphology*.

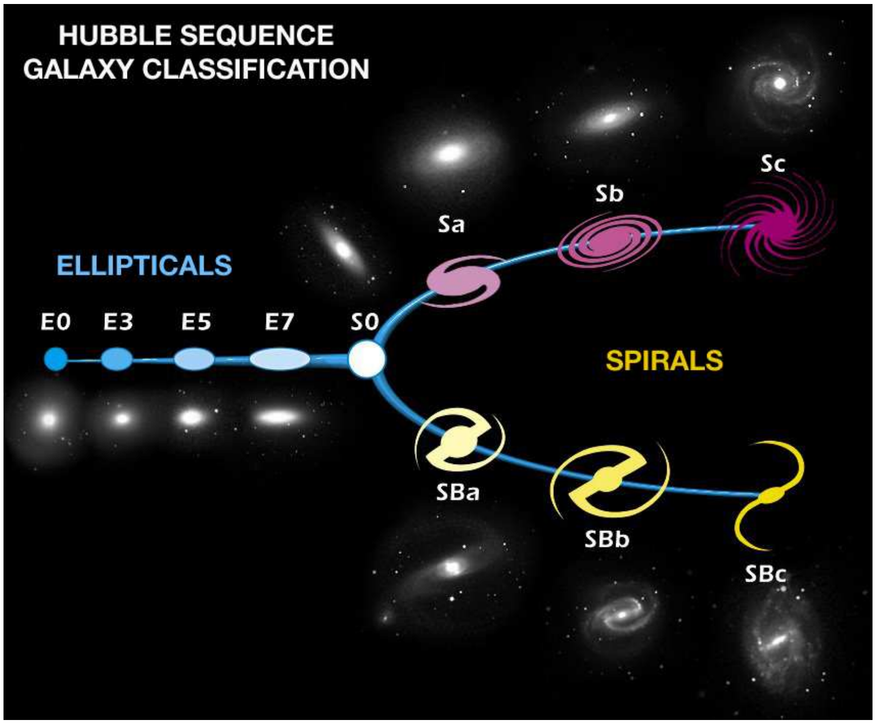
- There are 4 fundamental types of galaxies: *spirals* (denoted S), *barred spirals* (denoted SB), *ellipticals* (denoted E), and *irregulars* (denoted Irr).

- The denotations each are followed by an extra notation. The ellipticals are tagged with an integer n that represents the ellipticity of the galaxy on the sky ($E0$ are round, where as $E7$ are highly elliptical). Spiral galaxies are tagged with a letter a, b or c that characterizes how tightly wrapped the spiral arms are ((Sa or SBa are tightly wound, whereas Sc or SBc are loosely wound).

- In addition there is a special type $S0$ known as *lenticular galaxies* — these are galaxies with a bright central bulge and what appears to be an extended disk, but they have no discernible spiral structure.

- ***The Milky Way is type SBc.***

- Hubble arranged the galaxy morphologies into his famous Tuning Fork Diagram, which he imagined to represent galactic evolution.



- Hubble believed the Tuning Fork could represent the evolution of galaxies from ellipticals into spirals. In fact we know today that the evolution cannot happen, owing to the conservation of angular momentum — ellipticals have low angular momentum compares to spirals. We now believe that spirals evolve into ellipticals via randomly oriented mergers.

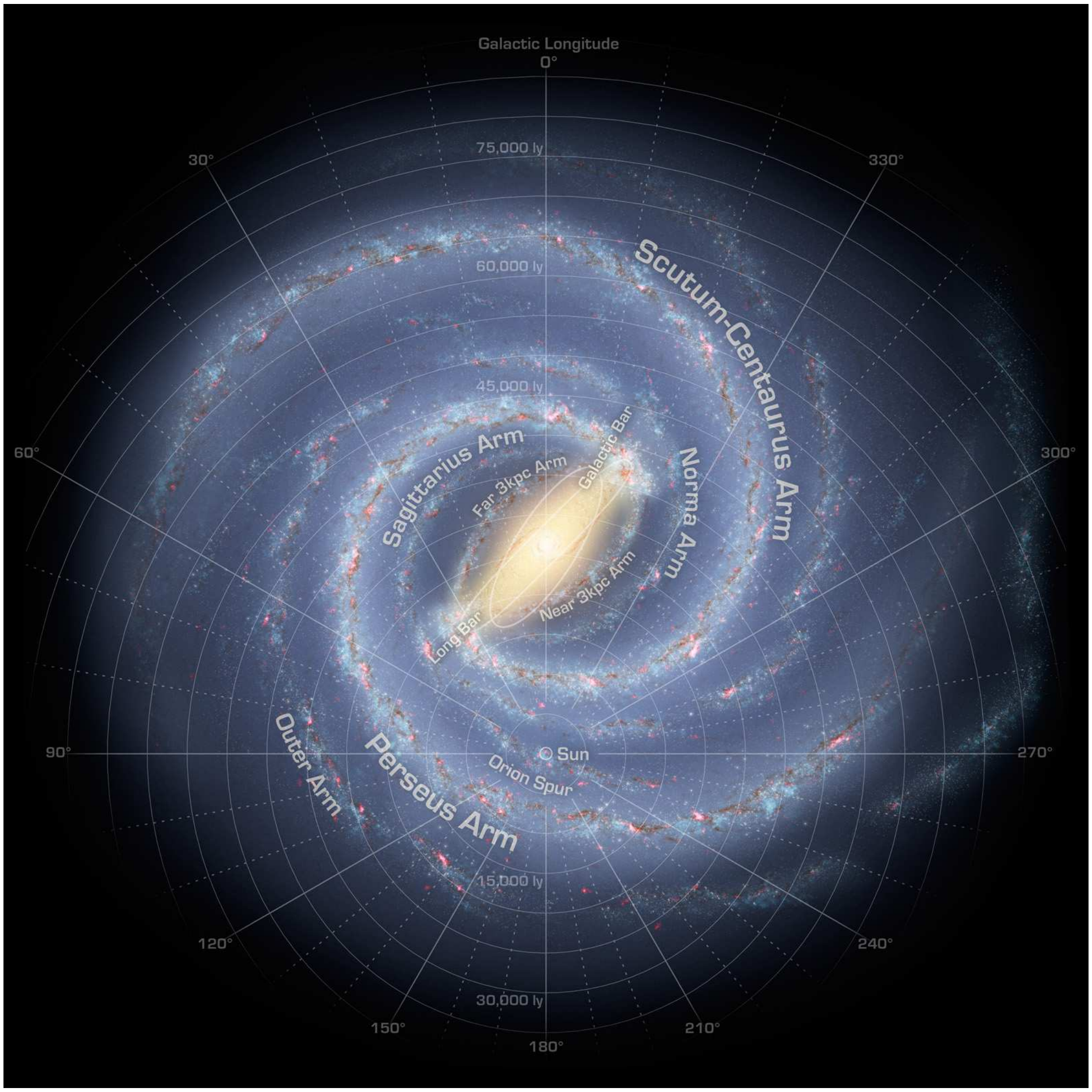
Galactic Coordinates

- In order to locate objects on the sky, astronomers work with coordinate systems. The coordinate systems of choice are usually on the sky, so are two-dimensional and specified by two angles. Distances are sometimes tacked onto these systems, making them three-dimensional spherical coordinate systems with the Earth at the origin.

- As you might imagine, there are many different standards, but three are most prominent:
  - ▷ ***Equatorial Coordinates***. These are called *right ascension* (RA or α) and *declination* (DEC or δ). The poles of this system sit over the poles defined by the Earth's spin.
  - ▷ ***Ecliptic Coordinates***. These are called *ecliptic longitude* and *ecliptic latitude.* The poles are defined by the angular momentum vector of the Earth's orbit.
  - ▷ ***Galactic Coordinates***. These are called *galactic longitude* and *galactic latitude.* The equator of this system is defined to lie along the Milky Way in the sky.

- Converting between these coordinate systems is a regular exercise in astronomy, and involves a great deal of spherical trigonometry and rotation of coordinates.

- The origin of galactic longitude is defined to be the direction toward the galactic center.



- There are two related galactic coordinate systems: one centered on the Sun (*heliocentric galactic coordinates*), and one centered on the Milky Way core (*galactocentric coordinates*). Astronomers (observers) tend to use heliocentric coordinates, whereas modelers often work in galactocentric coordinates.

Missing Mass

- In 1933 Fritz Zwicky was studying the Coma Cluster of galaxies. He could measure the motion of the individual galaxies and from the Doppler Shift, obtain the velocities. He assumed that all the light was coming from stars and that stars dominated the mass of the galaxy (*i.e.* gas was negligible), so *measuring the total light was approximate to measuring the mass.*

- With this information in hand, it is a straightforward matter to do an escape velocity calculation. Escape velocity is the velocity needed such that the kinetic energy is just large enough that it will go to zero at infinity. Remember that our definition of the gravitational potential energy, U_E goes to zero at infinity, so

$$K_E = U_E \qquad \rightarrow \qquad \frac{1}{2}mv^2 = G\frac{M_{gx}m}{r} \qquad \rightarrow \qquad v_{esc} = \sqrt{\frac{2GM_{gx}}{r}}$$

- What Zwicky discovered was that $v > v_{esc}$! The Coma Cluster should have flown apart long ago, but it was still holding together.

- The only conclusion was there was some *missing mass* that wasn't accounted for by the light – over 90%! By the 1970s, we had developed new kinds of astronomy using other wavebands (radio, IR, UV), but none of these efforts ever could account for any missing mass. This became known as *The Missing Mass Problem.*

Galaxy Rotation Curves

- One can use Kepler III to make a prediction about what the velocity profile of a galaxy should look like. If one makes the simplifying assumption that all stars in circular orbits around the galactic center, and that most of the mass of the galaxy M_{gx} is concentrated near the center (not entirely true, but a reasonable approximation for stars on the fringes, like the Sun), then

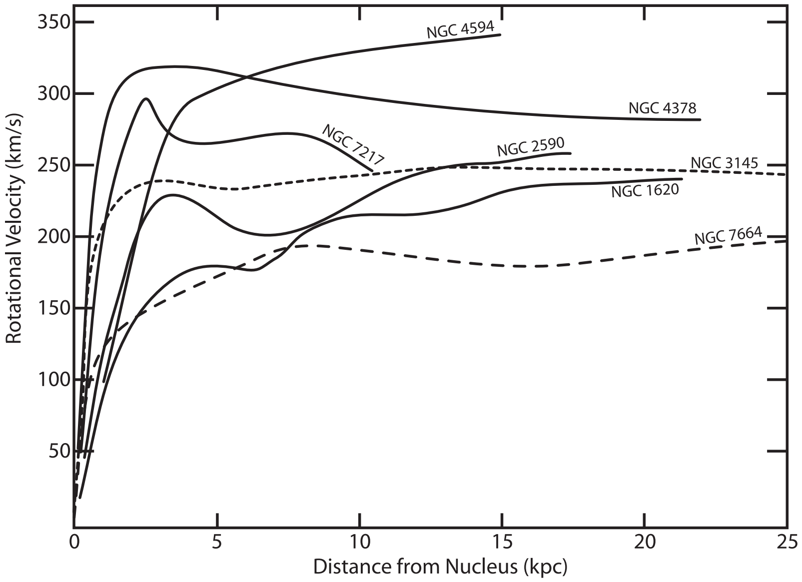
$$GM_{gx} = \frac{4\pi^2}{P^2}a^3 \qquad \rightarrow \qquad P = \sqrt{\frac{4\pi^2}{GM_{gx}}a^3} = 2\pi\sqrt{\frac{a^3}{GM_{gx}}}$$

- Defining the orbital speed to be the circumference of an orbit, $2\pi a$ divided by the orbital period from Kepler III we have

$$v_{orb} = \frac{2\pi a}{P} = \sqrt{\frac{GM_{gx}}{a}}$$

- This tells us we expect the velocity to fall off like $a^{-1/2}$.

- In the 1970s, Vera Rubin did what all good scientists do — she tested this prediction! She measured the speed as a function of radius for many galaxies and plotted the result — this is called a *galaxy rotation curve.* Several examples are shown below.



- These curves *do not* fall off! They are known as flat rotation curves, and are a generic feature of galaxies. What causes this?

- Suppose I solve Kepler III for the mass of the galaxy

$$GM_{gx} = \frac{4\pi^2}{P^2}a^3 \qquad \rightarrow \qquad M_{gx} = \frac{(2\pi a)^2}{P^2} \cdot \frac{a}{G}$$

- Combining this with the definition of circular speed

$$v_{orb} = \frac{2\pi a}{P} \qquad \rightarrow \qquad M_{gx} = \frac{v^2 a}{G}$$

- If $v(a) = const$, then this tells us that *the mass of the galaxy must increase linearly with the distance a from the center!* Alternatively you could make a statement of the density profile, $\rho(a)$. At the level of twiddles

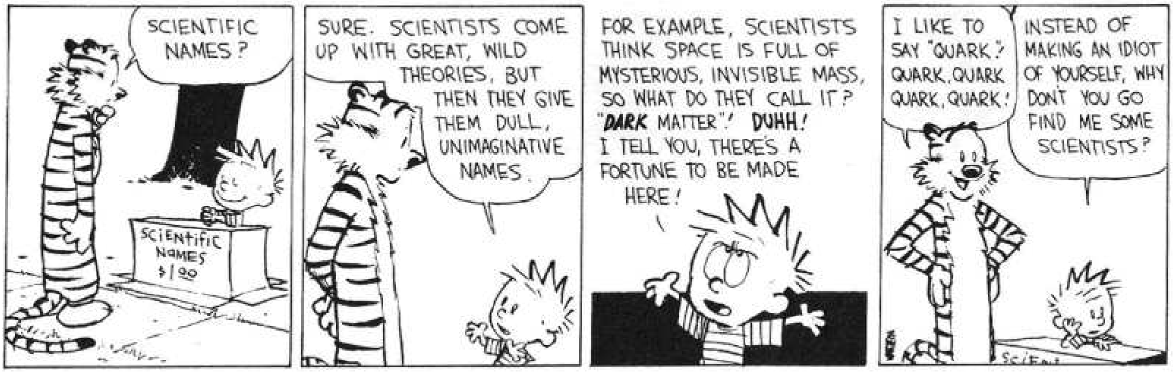
$$\rho \sim \frac{M_{gx}}{a^3} \sim \frac{v^2}{Ga^2}$$

so the density falls off like $1/a^2$.

- This is clearly not what we see when we look at a galaxy — the light falls off as you go from the center of the galaxy toward the edge, so *if the matter is not shining, it must be dark!* We imaginatively call this ***dark matter***.

Dark Matter

- Careful observations and analysis of distant galaxies in the Universe reveals several paradoxes concerning our knowledge of the masses of galaxies. Other conundrums include:



▷ Velocities of galaxies in binary systems exceed the maximum permissible values for gravitational binding. To remain bound to each other, these galaxies must have considerably more mass than their luminosity reveals.

▷ Random velocities of rich clusters of galaxies are so large that they would be unbound unless their total mass was *at least* **ten times larger** than the mass indicated by the luminosity of their component galaxies.

▷ The rotational curves of spiral galaxies (rotation speed versus distance from the galactic center) deviates considerably from what would be expected if galactic mass coincided with luminous matter.

• These apparent paradoxes are traditionally called the *Missing Mass Problem*, though modern astrophysicists almost uniformly accept the existence of dark matter.

• The existence of dark matter and the resolution of these apparent paradoxes may have significant cosmological implications, both in assessing the ultimate fate of the Universe and in our understanding of the fundamental nature of matter that makes up the Universe.

• The current census of the makeup of the Cosmos suggests that ordinary matter (atoms; stuff that makes light) only constitutes about 4% of the total amount of *stuff* out there. Some 23% is dark matter, and the rest is very likely another poorly understood cosmic constituent that goes by the prosaic name *dark energy.*

Galactic Haloes/Globular Clusters

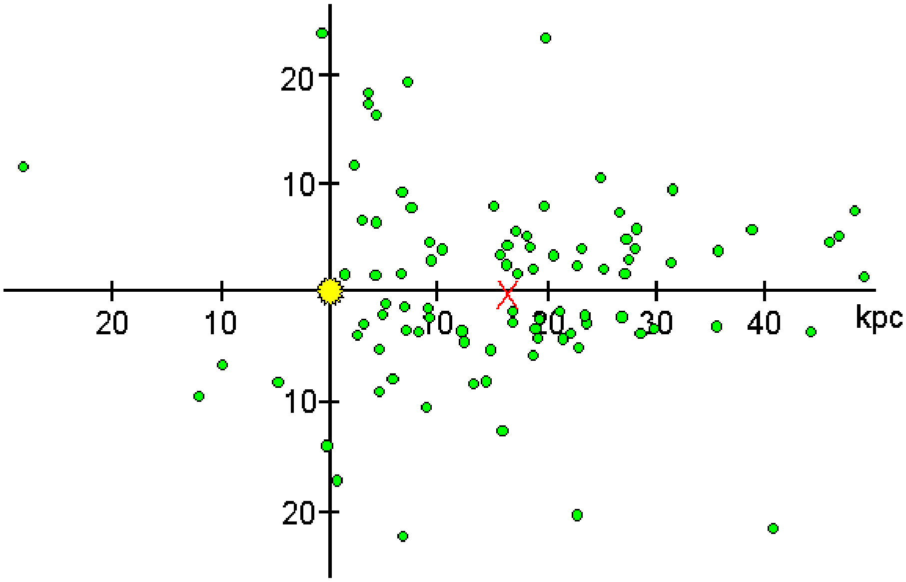
• Where is all the dark matter? Given the uniformity of its effect, we believe it is distributed in a vast, spherical bubble around the galaxy called *the halo.*

• The halo has been known about for a long time, because there are many other things in the halo, including stars and most notably the *globular clusters*

• After the first globular cluster was discovered, many more were recognized. Today we know that there are 157 globular clusters around the Milky Way.

- The common, identifiable characteristics of globular clusters include
  - They are bound to and orbit the Milky Way. We see globular clusters around other galaxies as well (you can see the globular clusters of M31 from your backyard with a 12” telescope if you try).
  - They are generally *round*; with large populations of stars ($N \sim 10^5 - 10^6$) they have enough self-gravity to give them their shape.
  - The high stellar density means they are *gravitationally bound* (they will never fly apart).
  - They have *low metallicity.* We take this to mean that they are an older generation of stars (usually called *Population II* stars) whose formation was not dominated by the (metal enriched) ashes of a previous generation of stars. Based on our understanding of stellar evolution, we believe the globular clusters in the Milky Way to be $\sim 10^{10}$ years old.

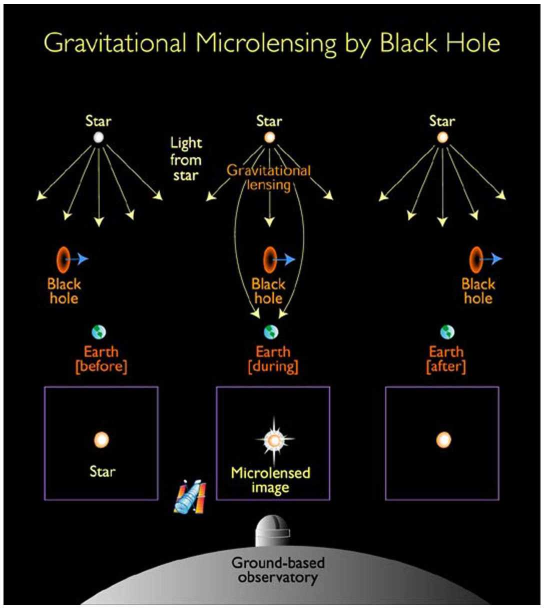
- The first person to seriously study the distribution of the globular clusters was Harlow Shapley. Using a population of Cepheids, he measured the distance to the globular clusters from Earth, and go a plot like the following



- If one assumes the globular clusters orbit the center of the Milky Way, then at any given moment they should be randomly distributed around that center. Looking at Shapley’s map, it is clear that the center of the galaxy is well away from the Sun. *this was the first time the position of the Sun in the galaxy had been measured!*

What is the Dark Matter?

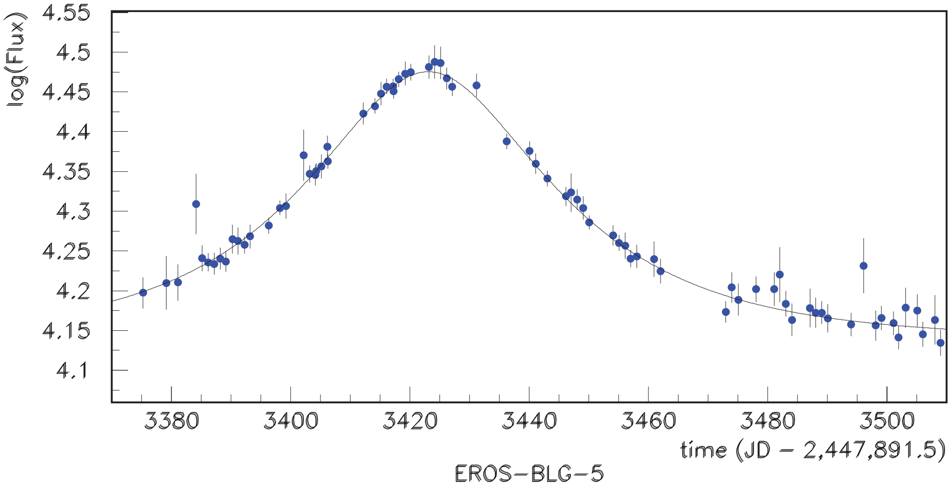
- There have traditionally been two camps of thought about the nature of the dark matter in the halo: it could be concentrated into compact, large objects, or it could be highly diffuse. These two possibilities have been opposed to each other, as evidenced by their names: the MACHOs vs. the WIMPs.



• MACHOs are *Massive Astrophysical Compact Halo Objects*. The premise is that the halo of the galaxy is filled with compact, dark objects (such as small black holes). How would you detect such things?

• If the halo were full of MACHOs, then if you were to watch a distant stellar system (such as the Large Magellanic Cloud), then periodically a MACHO would pass in front of or near to one of the stars in the distant system. The result is *gravitational microlensing* — the MACHO acts like a lens, focusing light toward the Earth by gravitationally bending the trajectories.

• From the perspective of viewers on Earth, if we are measuring the brightness of a distant star as a function of time, we see the brightness rise then fall with a characteristic shape. The time of the rise and fall is indicative of the speed of the MACHO (nominally a measure of its position in the halo) and the amplification is a measure of the MACHO mass. An example curve is shown below (from Afonso et al., A&A **404**, 145 [2003]).



• Two extensive observing campaigns to search for MACHOs have been carried out, by the MACHO Collaboration (Alcock et al., ApJ **542**, 281[2000]) and the EROS Collaboration (Tisserand et al., A&A **469**, 387 [2007]).

• These projects monitored tens of millions of stars in the Large Magellanic Cloud for the greater part of a decade, looking for microlensing events from MACHOs.

• The MACHO Collaboration found 17 microlensing events, and determined the halo mass in MACHOs (out to 50 kpc) to be $\sim 9 \times 10^{10} M_\odot$ (about 20% of the total halo mass), with the most likely mass range of a MACHO to be: $0.15 M_\odot \lesssim m \lesssim 0.9 M_\odot$.

- The EROS Collaboration used a much more restricted sample of stars and saw only 1 microlensing event. They estimate the halo mass in MACHOs is less than $\sim 8\%$ of the total halo mass, with the most likely mass range of: $0.6 \times 10^{-7} M_\odot \lesssim m \lesssim 15 M_\odot$.

- It seems clear from these results that some of the dark halo could be made up of MACHOs, but not all of it.

- A competing idea is that the dark matter are WIMPs — *Weakly Interacting Massive Particles*. The premise is that the halo of the galaxy is filled by a gas of massive fundamental particles which have up to now forgone detection because they interact very poorly with other forms of matter (like the stuff our detectors are made of!). They do, however, very readily interact via gravitational interaction by virtue of their mass-energy.

- There are two flavors of WIMPs that could be the dark matter: *hot dark matter* and *cold dark matter*.

- Hot dark matter are WIMPs with ultra-relativistic speeds, by virtue of their high energy origins and relatively light mass. A leading candidate for HDM are *neutrinos*, however they are generically not favored because numerical simulations of the formation of large scale structure in the Universe suggest that HDM would smear out the structure we see in the galaxy distributions, conflicting with our current best observations.

- Cold dark matter are WIMPs that are heavy and slow moving[1]. Most CDM candidates are expected to interact not only via the gravitational force, but also via the *weak nuclear force*, so experimental efforts are focused on precise weak nuclear interaction measurements, looking for the tell-tale signatures of an interaction with a dark matter particle.

- There are no universally agreed upon candidates for WIMPs. Within the Standard Model of particle physics, all the expected particles have been experimentally found and accounted for. One of the leading candidates is a particle known as the *axion*, a hypothetical particle that was suggested to exist as a way to explain some unresolved problems in particle physics (in the case of the axion, the "strong CP problem" in quantum chromodynamics). Other candidates come from *super-symmetric theories*, extensions of the Standard Model that propose the existence of an entire scaffold of particles that are companions to the known particles (and as of yet completely undetected!).

- There is one truth about the search for WIMPs: there are a lot of theoretical ideas, but we don't know what we are looking for so experimental searches are hard!

- Despite good success with CDM theoretically explaining the large scale structure we see, there are still a variety of problems with CDM that need resolution, particularly with regards to galaxies. The most pressing are:

  - ▷ Dwarf satellites. CDM paradigms predict that galaxies like the Milky Way should have a large number of small satellite galaxies (dwarf satellites, which have only $\sim 0.1\%$ the

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[1] MACHOs are a form of Cold Dark Matter, though as we have seen they are not favored to be the dominant form of dark matter.

mass of the Milky Way). Only a fraction of the expected number are observed; in the Local Group there are about 38 known dwarfs, with 11 orbiting the Milky Way. CDM predictions suggest there could be as many as 500 around Milky Way

- ▷ Galactic Dark Matter Distribution. CDM paradigms predict that the dark matter distribution should be more strongly peaked (*cuspy* in astronomer language) near the center of galaxies than what is observed. By contrast, if you look at the Milky Way and other spirals, it seems there is no cusp (peak) in the dark matter distribution near the center at all!

• There is still intense debate and research about these problems, because there is other strong evidence that CDM is the correct form of dark matter. Much of the debate centers on the ideas that: (1) perhaps we don't have all the physics in place yet about interactions between galaxies, the dark matter, and stellar populations (2) perhaps our simulations about the effect of CDM are wrong.