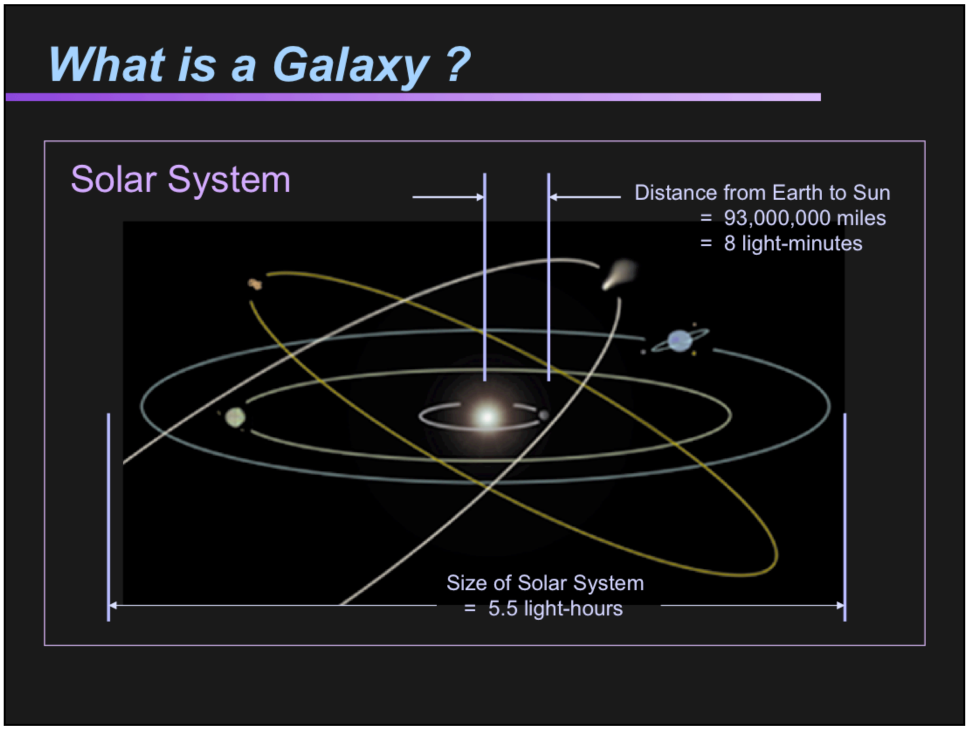
In this presentation, we'll discuss the information about galaxies contained in "The Hidden Lives of Galaxies" poster and information booklet. We'll also do a couple of classroom activities discussed in the booklet

This version of the presentation includes information on galaxy formation, and has expanded approach for determining that galaxies have hidden mass

[An image of the poster and text of the booklet are available on-line at http://imagine.gsfc.nasa.gov/docs/teachers/galaxies/galaxies.html]

This version was uploaded to the Imagine site on 8/28/03 under the name

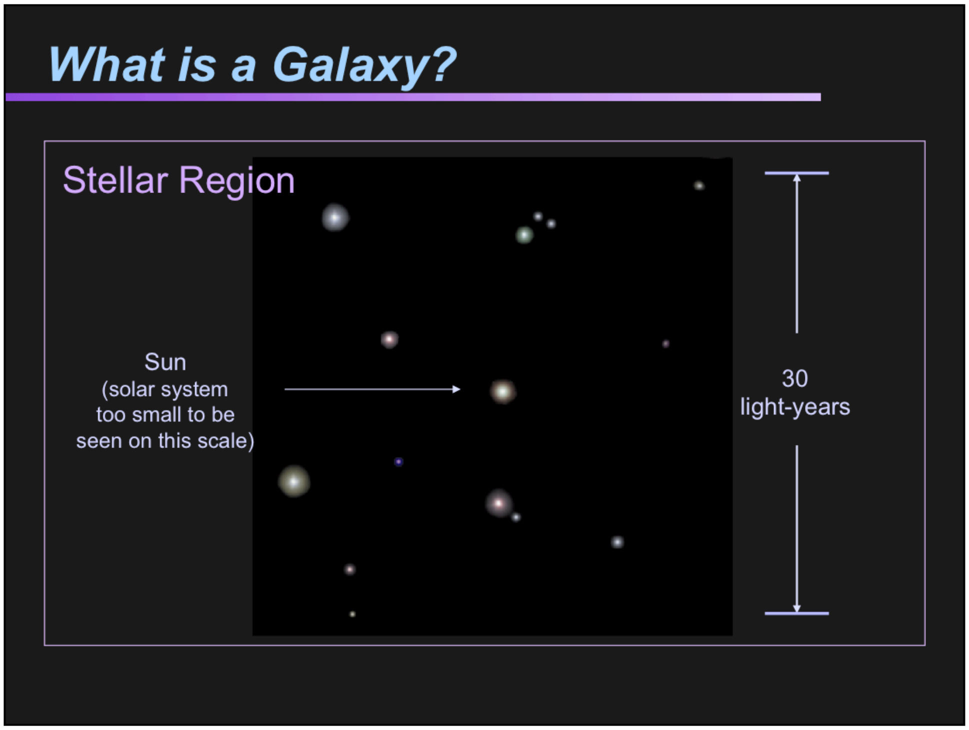
Hidden_Lives_v2.ppt



To define what a galaxy is, we start with something close to home - our own solar system - and its place in our galaxy.

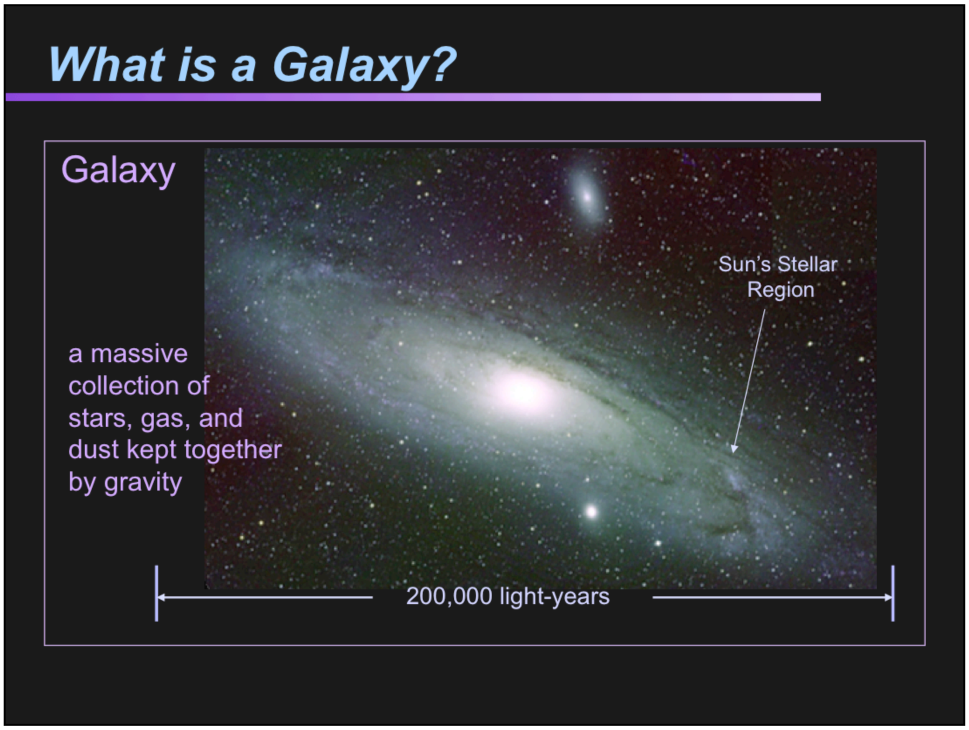
The distance from the Earth to the Sun is 93 million miles (150 million km), or 8 light-minutes. That is, the time it takes light from the sun to reach Earth is 8 minutes.

The entire solar system is 5.5 light-hours across. That is, light takes 5.5 hours to cross the solar system.



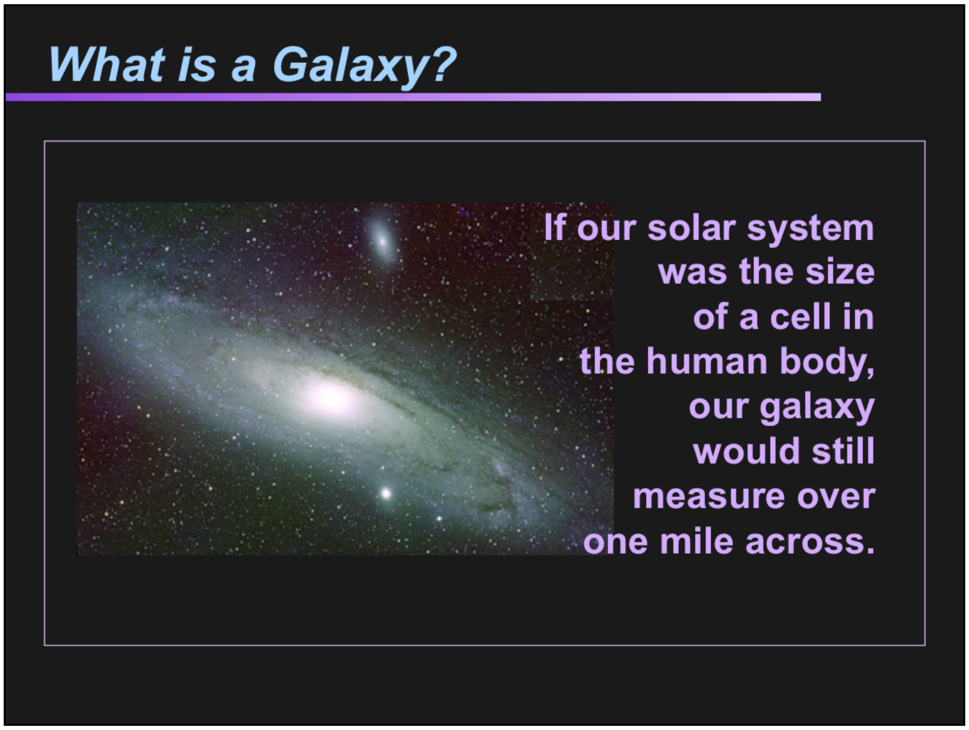
Neighboring stars can be grouped into stellar regions. The solar neighborhood is about 30 light-years across. A light year is the distance light travels in one year, and is about 6 trillion miles (9.5 trillion km)

[Note that in some regions stars can be clustered quite closely together. Thus, some neighborhoods may be more crowded than others.]



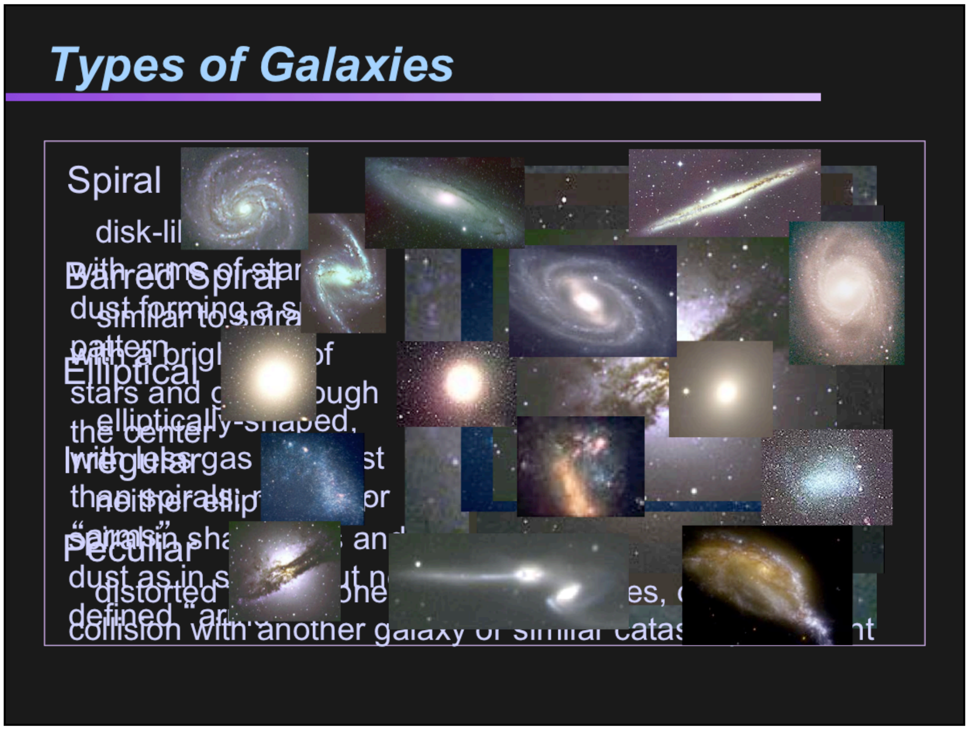
A stellar region is just a small portion of a galaxy. A galaxy is a massive collection of stars, gas, and dust held together by its own gravity. Galaxies can range in size from 6,000 to 350,000 light-years across. Our own galaxy, the Milky Way, is about 105,000 light-years in diameter.

The galaxy pictured here is the Andromeda Galaxy, which is the nearest large galaxy to our own. We think the Milky Way looks very much like Andromeda.



Galaxies are enormous in size. This slide shows the scale of our galaxy by analogy to the size of a cell in the human body. [A cell in the human body is about 50 microns (or 0.00005 meters) across.]

Using this same analogy, the Andromeda Galaxy would be 22 miles away.



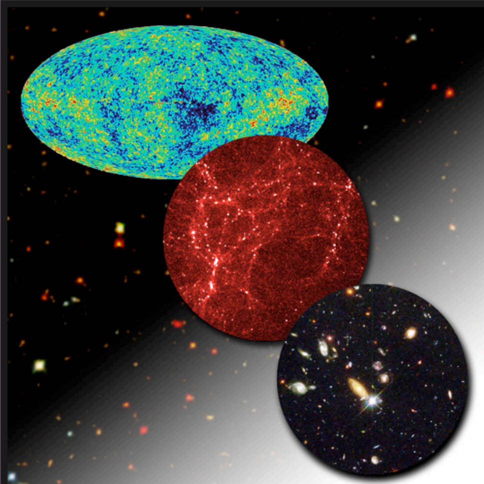
There are different types of galaxies, each with different characteristics.

This slide presents the different galaxy types and their major features, one at time. The slide ends by showing a few additional examples of each type of galaxy.

[This version works properly in Powerpoint for Mac OS X. The large image of the galaxy is now grouped with its descriptive text.]

At this point, participants can perform Activity #2 from "The Hidden Lives of Galaxies" booklet to test their knowledge of the types of galaxies. Use Transparencies #1 and #2 which accompany the booklet or which are available on the Imagine the Universe! website at http://imagine.gsfc.nasa.gov/docs/teachers/galaxies/transparencies/

Galaxy Formation



Galaxies form from the primordial density fluctuations that arise after the big bang and grow under inflation.

These density fluctuations form filaments, and galaxies form in knots along the filaments.

This is according to http://zeus.ncsa.uiuc.edu:8080/Summers/galform.html

Note that a bottom up theory still exits. Matter clumps on smaller scales and then becomes bound together into a galaxy.

Spirals vs. Ellipticals

Final type of galaxy depends on initial rate of star formation:

- If stars form quickly, then galaxy becomes elliptical. Stars form within initial distribution of gas,and follow their initial orbits.
- If stars form later, the gas has time to collapse into a disk. Most stars from within the disk. The galaxy becomes a spiral.

Gas dissipates energy through collisions. Atoms in gas collide and heat up. The heat is dissipated in the infrared. The gas thus loses energy and collapses. If stars form quickly, then galaxy becomes elliptical. Angular momentum forms the gas into a disk.

In ellipticals, gas hasn't had time to collapse into a disk, and stars retain their initial orbits.

If star formation proceeds more slowly, then the gas undergoes collisions and forms a disk under conservation of angular momentum. The stars don't form until gas has collapsed into the disk.

Globular clusters seem to form in the first epoch of star formation, just as the galaxies are forming.

From http://zebu.uoregon.edu/~js/ast123/lectures/lec27.html

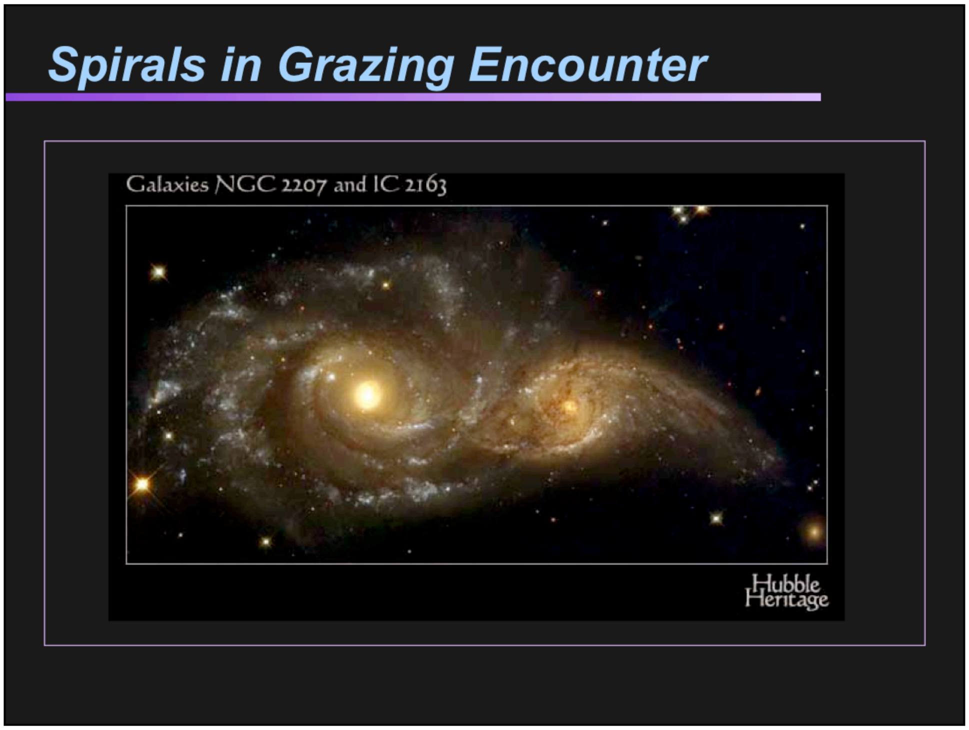
Formation via Galaxy Mergers

In clusters, galaxies can pass close to one another.

- Galaxies can become distorted, and often merge.
- Mergers often lead to giant elliptical galaxies at the heart of large clusters.

Mergers occur because the universe is actually pretty crowded ! From http://stardate.org/resources/galaxy/formation.html: “Mergers are common because the universe is crowded, at least on the galactic distance scale. The disk of the Milky Way, for example, spans about 100,000 light-years; the nearest major galaxy, the great spiral in Andromeda, lies about two million light-years away. That means the distance between these two galaxies is only about 20 times greater than the sizes of the galaxies themselves. That doesn't leave a lot of "elbow room" for galaxies.”

See http://www.strw.leidenuniv.nl/~dokkum/mergers/info_eng.txt for nifty info about mergers. E.g it can take only a billion years for a merger to be complete.



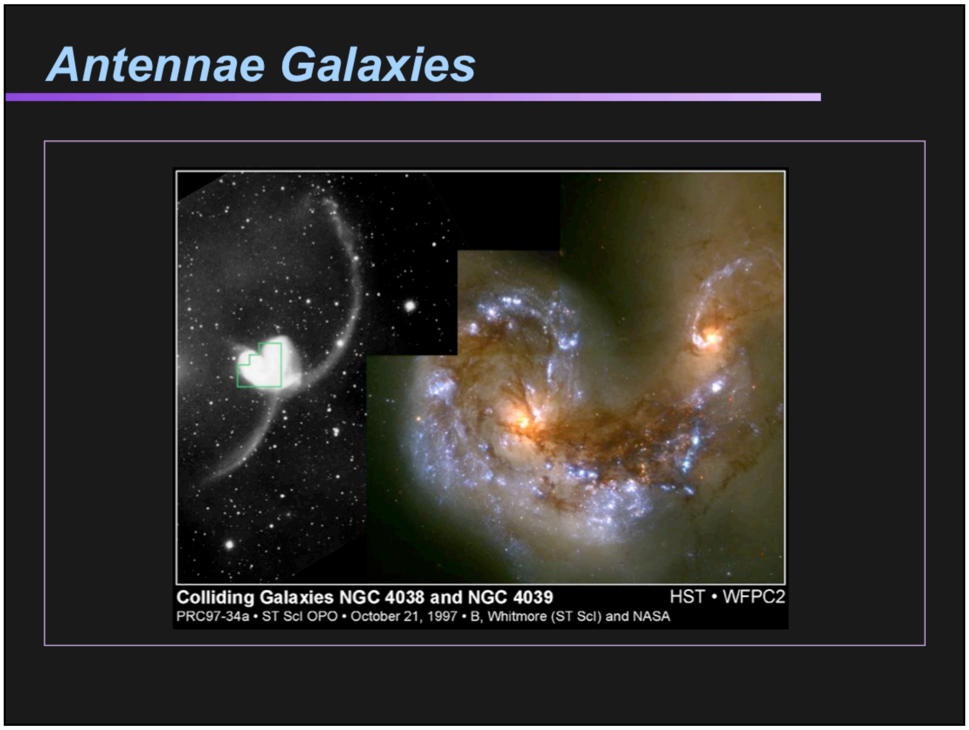
From http://heritage.stsci.edu/1999/41/index.html

Calculations indicate that IC 2163 is swinging past NGC 2207 in a counterclockwise direction, having made its closest approach 40 million years ago. However, IC 2163 does not have sufficient energy to escape from the gravitational pull of NGC 2207, and is destined to be pulled back and swing past the larger galaxy again in the future. They are destined to merge in the next few billion years.

NGC 2207 has a diameter of 143,000 light years (44 kpc or 4').

IC 2163 has a diameter of 101,000 light years (31 kpc or 3').

They are 114 million light years (35 megaparsecs) away



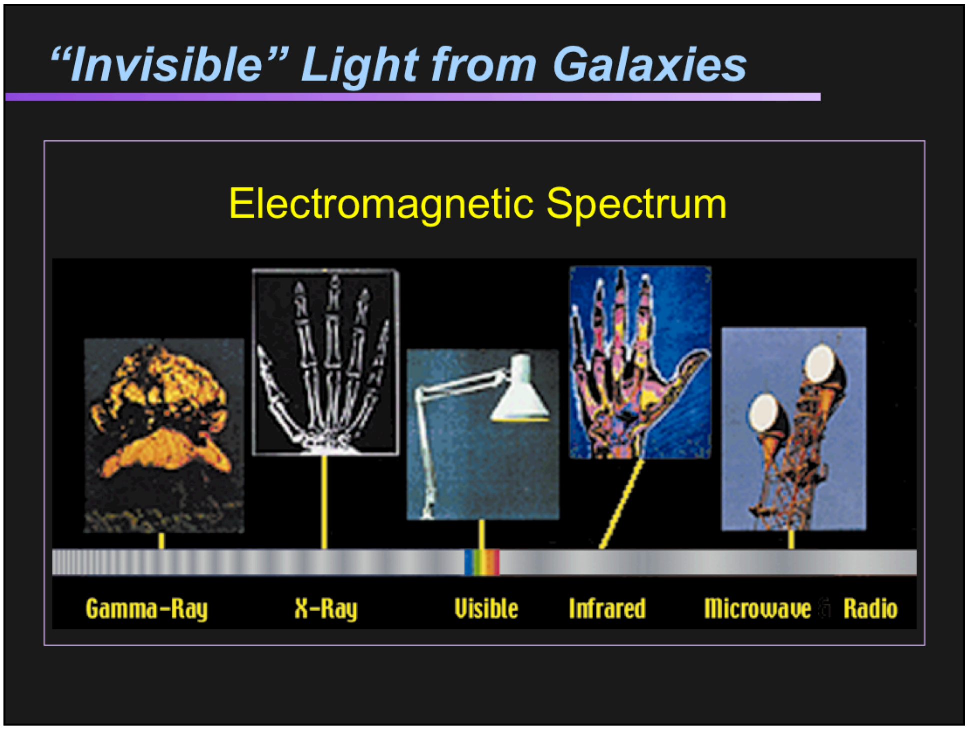
The collision of these two galaxies sparks star formation (via collision of gas clouds)

http://hubblesite.org/newscenter/archive/1997/34/

From the figure caption:

The Hubble telescope has uncovered over 1,000 bright; young star clusters bursting to life in a brief, intense, brilliant "fireworks show" at the heart of a pair of colliding galaxies.

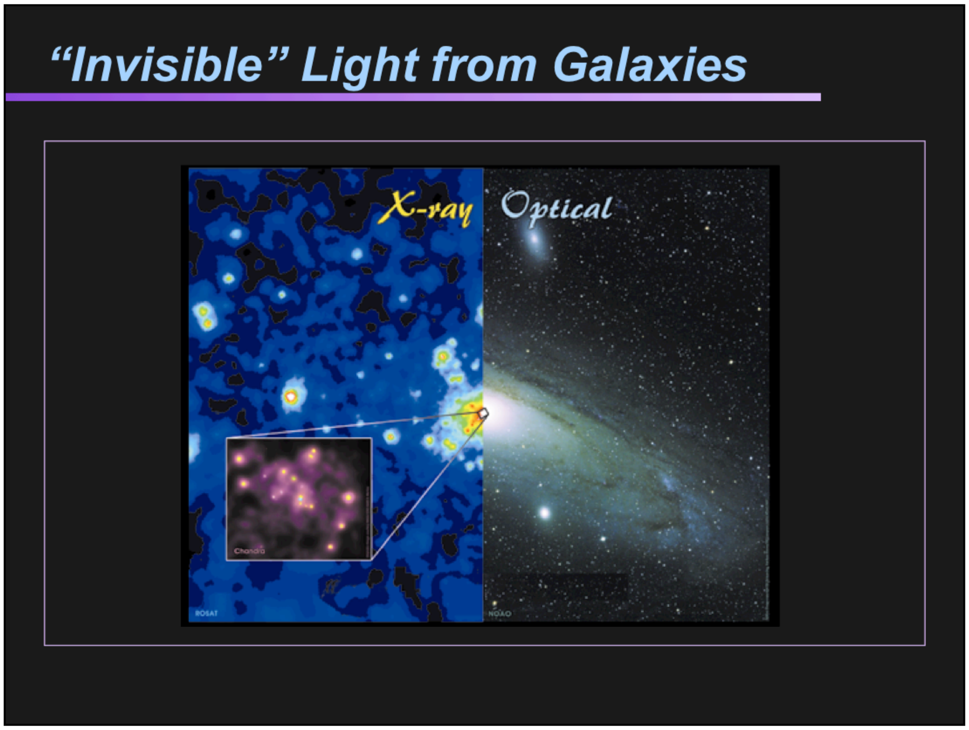
The picture on the left provides a sweeping view of the two galaxies, called the Antennae. The green shape pinpoints Hubble's view. Hubble's close-up view [right] provides a detailed look at the "fireworks" at the center of this wreck. The respective cores of the twin galaxies are the orange blobs, left and right of center, crisscrossed by filaments of dark dust. A wide band of chaotic dust stretches between the cores of the two galaxies. The sweeping spiral-like patterns, traced by bright blue star clusters, are the result of a firestorm of star birth that was triggered by the collision.



Light is not only what we see with our eyes, but also comes in the form of radio waves, microwaves, infrared, ultraviolet, x-rays and gamma-rays. This figure shows common images representing the major portions of the spectrum. The gradations on the gray scale represent the changing wavelength of light as it goes from gamma-ray to radio.

Astronomers use different regions of the e-m spectrum to determine different properties of objects. We often don't get the whole picture until we look at an object in different wavelengths.

Note that the X-ray image is not like the other images. The other images show the objects that emit that particular radiation. The medical x-ray show what is absorbed by the x-rays.

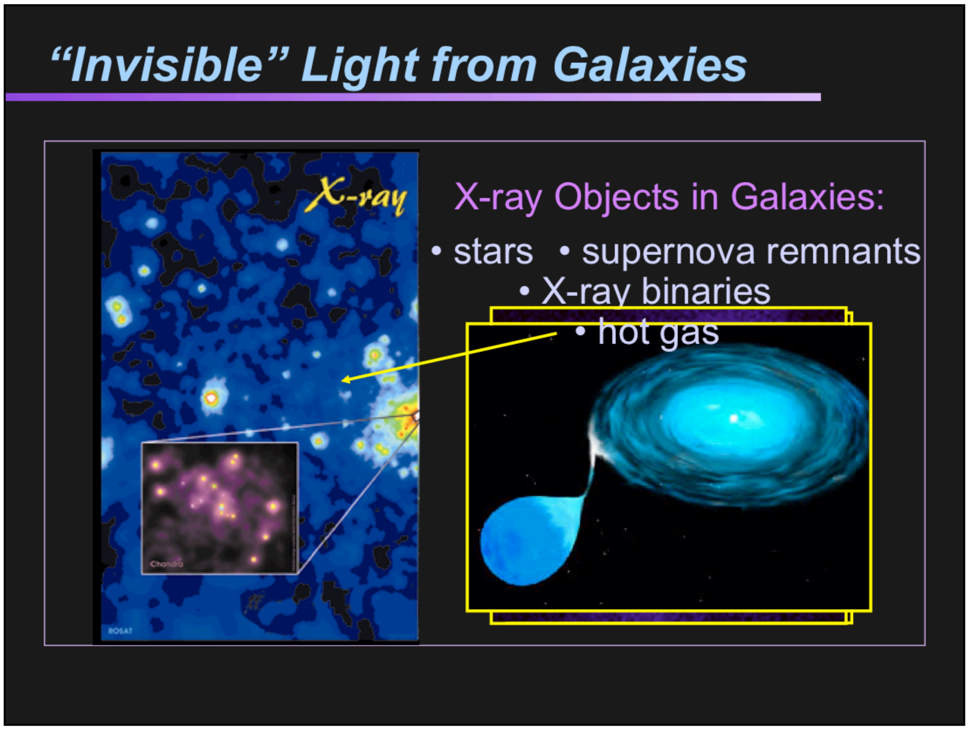


An X-ray picture of a galaxy looks very different from an optical picture.

On the right is an optical picture of the Andromeda Galaxy. Note the familiar spiral structure, and the dark lanes of dust.

On the left is an x-ray image of the Andromeda Galaxy taken by the ROSAT satellite. We no longer see the spiral structure, but instead individual objects.

The inset shows a close-up of the central region of the Andromeda Galaxy taken by the Chandra X-ray Observatory. Again we see individual sources. But in both the Chandra and ROSAT images, we also see diffuse x-ray emission caused by hot gas.



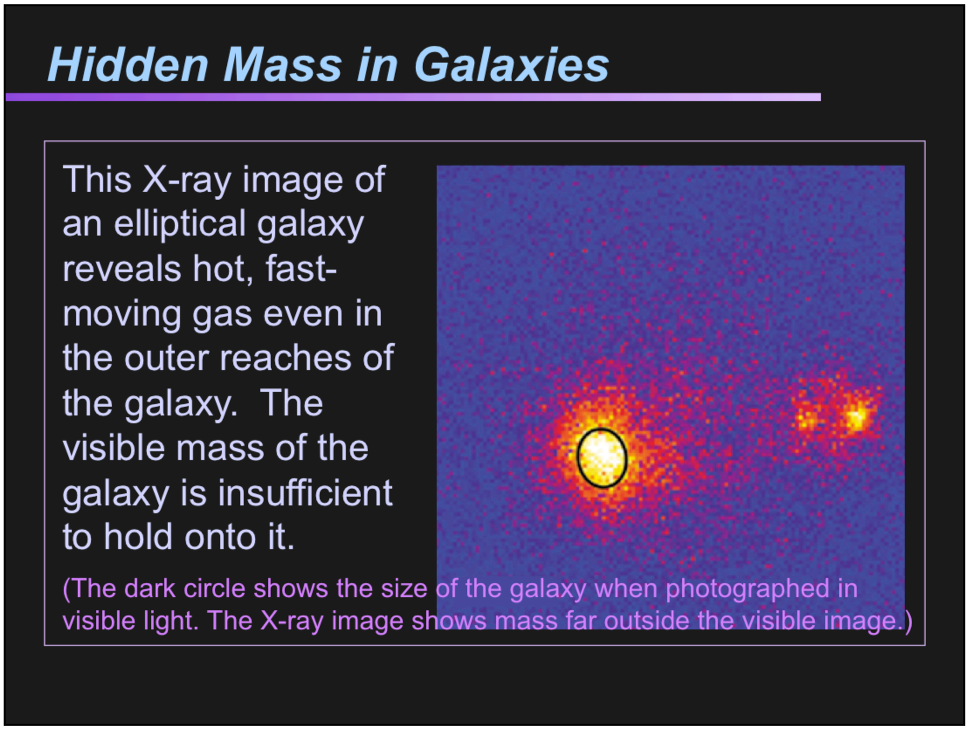
These are some of the objects that emit x-rays in a galaxy:

- Stars, like our Sun, emit X-rays from their hot coronas and active regions.

- A Supernova Remnant is the remains of a massive star that has exploded. The explosion emits a shock wave that heats up surrounding gas. The gas becomes hot enough to glow in X-rays.

- X-ray Binaries are star systems that consist of a normal star and a compact object such as a white dwarf, neutron star, or black hole. The compact object is what remains from a star after a supernova explosion. Material from the normal star flows toward the compact star, forming a disk of material around the compact star. As it nears the compact star, the gas in this disk becomes hot enough to emit x-rays.

- Hot Gas permeates the galaxy and can surround a galaxy.



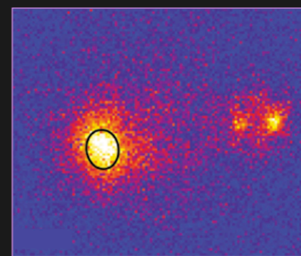
A number of elliptical galaxies are observed to have hot gas beyond the visible limits of the galaxy.

The temperature of the gas is a measure of its velocity and energy. This gas is so hot (about 10 million degrees Kelvin, or 18 million degrees F), and consequently has such a high velocity, that it first appears to be escaping from the galaxy. Indeed, the amount of visible mass in the galaxy is insufficient to keep it from escaping. We know the gas is bound to the galaxy, because if it wasn't it would have dissipated long ago. Hence, there must be some other matter that lies undetected in the galaxy. This additional matter gives the galaxy enough mass to hold onto the gas.

This “hidden mass” is also known to astronomers as “dark matter”.

Hidden Mass in Galaxies

So, we have a Problem:



- This gas gives off X-rays, which means it's *hot!*
- Hot gas moves at high velocities - we can measure and confirm this
- The velocity of the gas is greater than the escape velocity of the galaxy, if we calculate the galaxy's mass by adding up all the mass we can see at all wavelengths of light
- So why hasn't the gas escaped? There *must* be more mass we *can't* see!

Hidden Mass in Galaxies

Another way to look at the problem:

We can determine the mass of an object by measuring the motion of bodies in orbit around it.

Newton's Second Law: $F = ma$

F = Force of Gravity

a = acceleration due to circular motion

$$\frac{GMm}{r^2} = \frac{mv^2}{r}$$

Hidden Mass in Galaxies

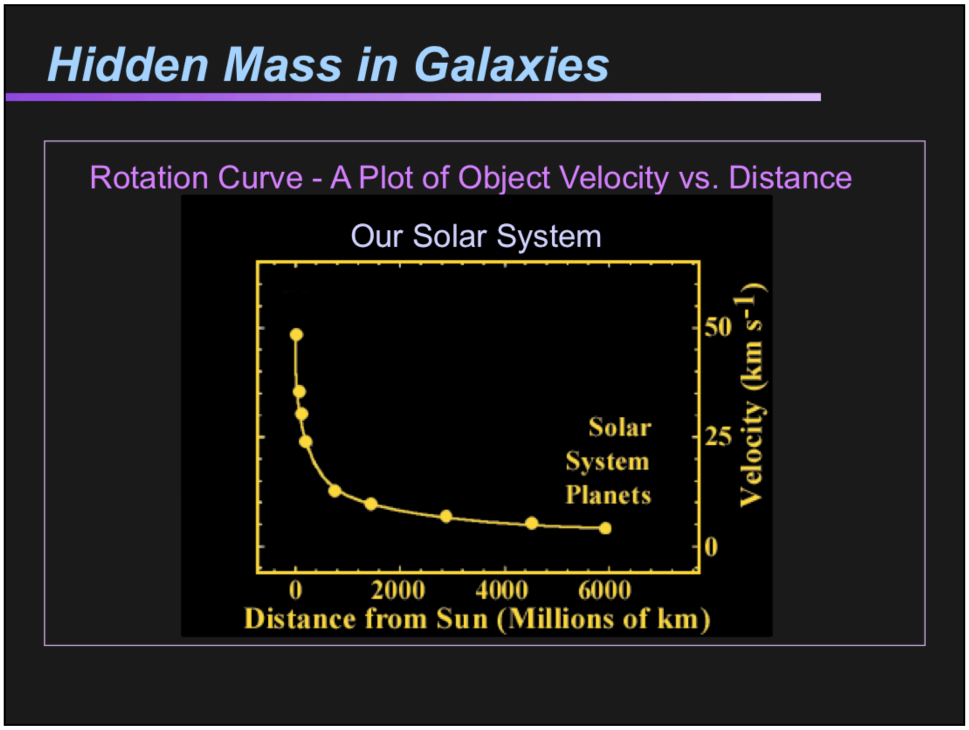
From previous slide, we have Newton's Second Law of Motion assuming a gravitational force and acceleration due to circular motion:

$$\frac{GMm}{r^2} = \frac{mv^2}{r}$$

Simplifying gives:

$$v^2 = \frac{GM}{r}$$

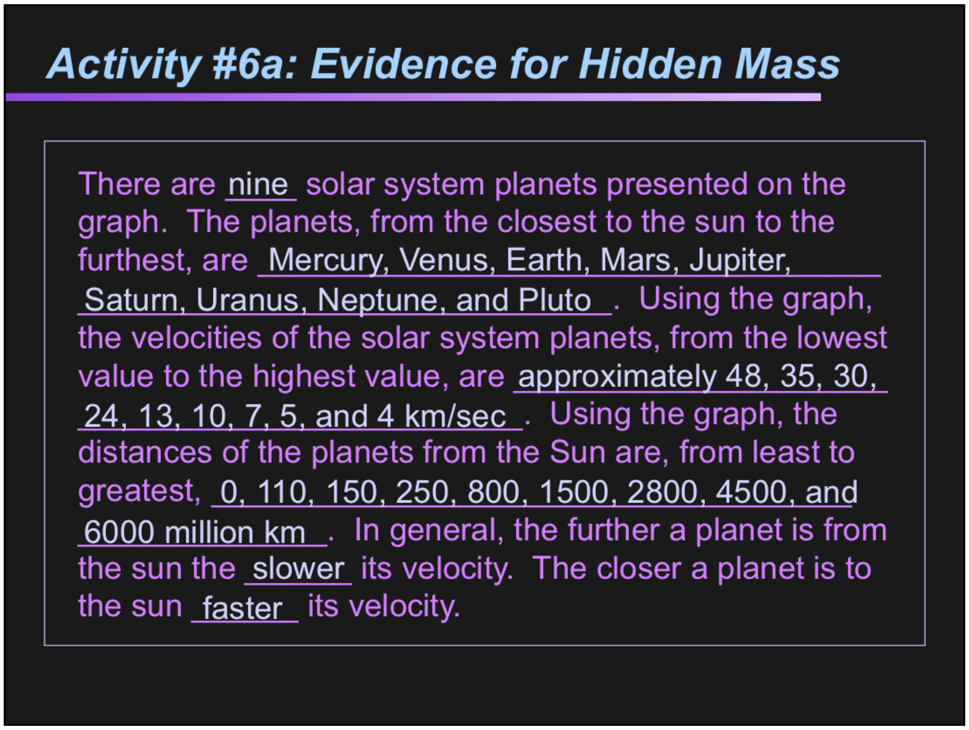
So, if *GM* is constant, then velocity is proportional to the inverse square root of distance. For example ...



To further understand the evidence for hidden mass in galaxies, we go back to examining our own solar system.

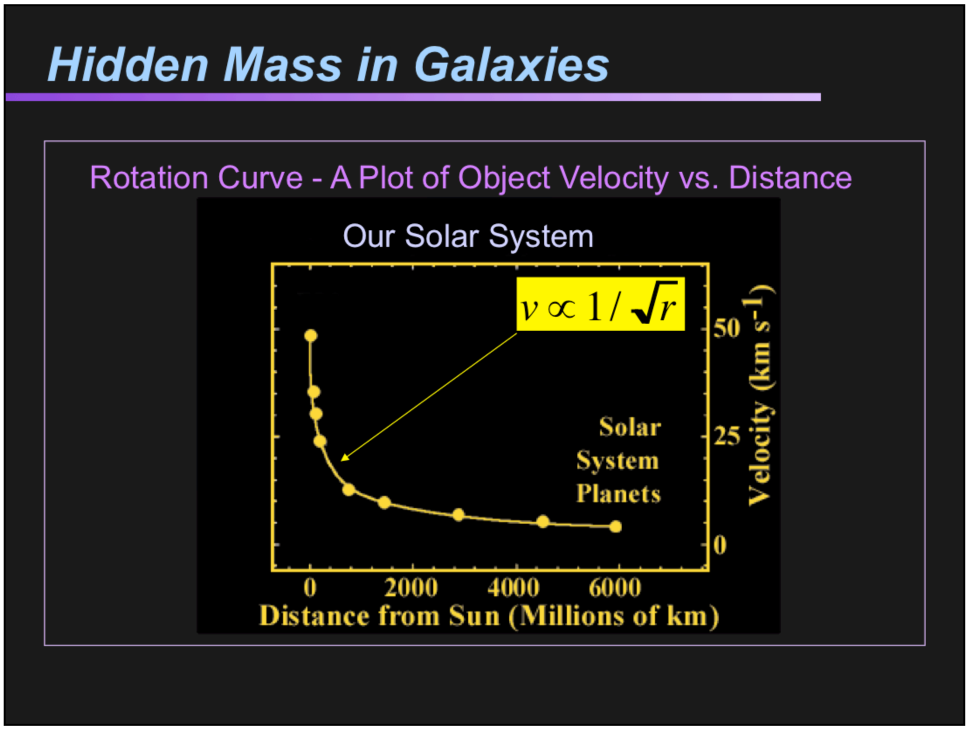
We first plot the velocity of the planets in their orbits around the sun (right hand vertical scale, in yellow) as a function of their distance from the sun (bottom scale, in yellow). This type of plot is known as a Rotation Curve. Ask audience members to describe how the velocity of the planets varies as the distance from the sun varies [as the distance increases, the velocity decreases].

You can use this slide with the following slide (on Activity 6a). May work best with this as a separate transparency on an overhead.



To better familiarize themselves with the rotation curve of the solar system, participants now perform the first part of Activity #6a in "The Hidden Lives of Galaxies Booklet." Use Transparency #6 which accompanies the booklet or which is available on the Imagine the Universe! website at http://imagine.gsfc.nasa.gov/docs/teachers/galaxies/transparencies/

When participants are done, the presenter uses this slide to fill in the answers.



To further understand the evidence for hidden mass in galaxies, we go back to examining our own solar system.

We first plot the velocity of the planets in their orbits around the sun (right hand vertical scale, in yellow) as a function of their distance from the sun (bottom scale, in yellow). This type of plot is known as a Rotation Curve. Ask audience members to describe how the velocity of the planets varies as the distance from the sun varies [as the distance increases, the velocity decreases]. The curve described is exactly that expected from Newton's Law of Gravity.

Hidden Mass in Galaxies

The previous plot showed data for planets in our solar system, illustrating the equation:

$$\boxed{v^2 = \frac{GM}{r}}$$

If we solve for M: $\boxed{M = v^2 r / G}$

We can use real data (the distances and velocities of the planets) and the fact that $G = 6.67 \times 10^{-11}\ m^3/kg\text{-}s^2$ to verify that the central mass, *M*, remains constant..

Activity 6b, part 1

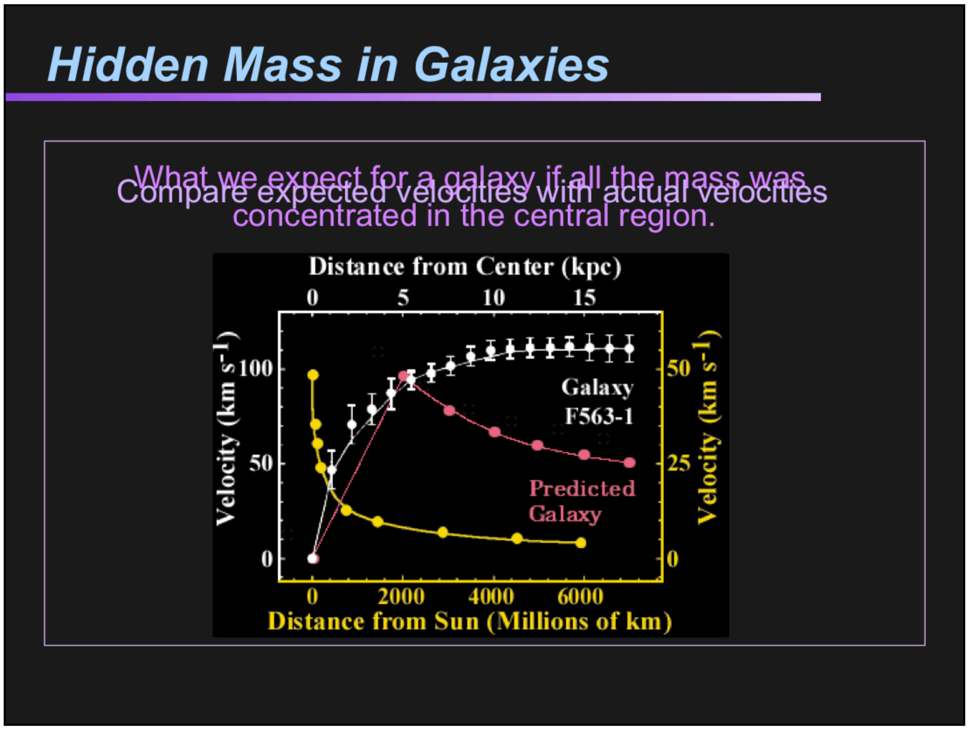
Planet	Distance from Sun (km)	Velocity (km/s)	Mass (kg)
Earth	1.5×10^8	29.8	2.0×10^{30}
Jupiter	7.8×10^8	13.1	2.0×10^{30}
Neptune	4.5×10^9	5.4	2.0×10^{30}

Hidden Mass in Galaxies

What does this have to do with Galaxies???

If we measure the distance and velocity of objects (eg., stars) orbiting in a galaxy, we'd expect them to obey the same laws. As distance from the center of the galaxy increases, we should get to a point where almost all of the galaxy's mass is inside the orbit of the furthest objects.

At this point, the central mass would be practically constant, and we would expect a rotation curve similar to that for our solar system.



We now compare the rotation curve for the solar system to that of a galaxy. Here we plot the velocities of stars going around the center of the galaxy (left hand vertical scale, in white) vs. their distance from the center of the galaxy (top scale, in white). “Kpc” stands for “kiloparsecs”, a distance used to measure large distances in galaxies (1 kpc = 3,260 light-years).

We expect the rotation curve of a galaxy to be linear through the central bulge. This is because the central bulge rotates as a solid body. Outside the bulge, we expect the rotation curve to fall off with distance according to Newton’s Law of Gravity (similar to the solar system).

Now show the actual rotation curve for a galaxy. Again, ask audience members to describe how the velocity varies as a function of distance [it rises steadily, and then at 10 kpc it becomes nearly constant]. We find that the velocities continue to rise outside the bulge, and eventually flatten out.

The fact that velocities don’t follow Newton’s Gravity means that there is more mass in the galaxy than we can account for.

Hidden Mass in Galaxies

If we take the same equation we used for the solar system:

$$M = v^2 r / G$$

and use the actual distances and velocities observed for this galaxy, we can calculate the enclosed mass at various distances from the galaxy's center.

(Remember that $G = 6.67 \times 10^{-11}$ $m^3/kg\text{-}s^2$)

Activity 6b, part 2

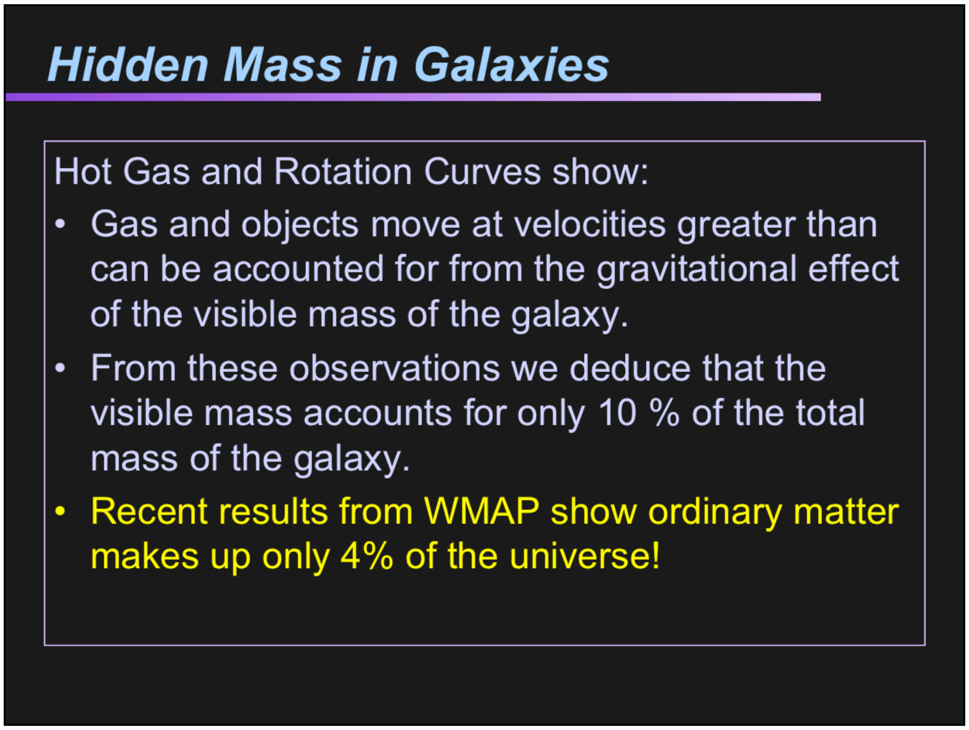
Distance (kpc)	Velocity (km/s)	Mass (kg)
5.0	95.0	2.1×10^{40}
10.0	110.0	5.6×10^{40}
15.0	110.0	8.4×10^{40}

Hidden Mass in Galaxies

What Happened?!?!?

The central mass never becomes constant, as it did for the Solar System. The fact that the mass is still increasing means we haven't yet reached a distance where all the mass is contained inside that orbit. But we've plotted *all the matter we see!*

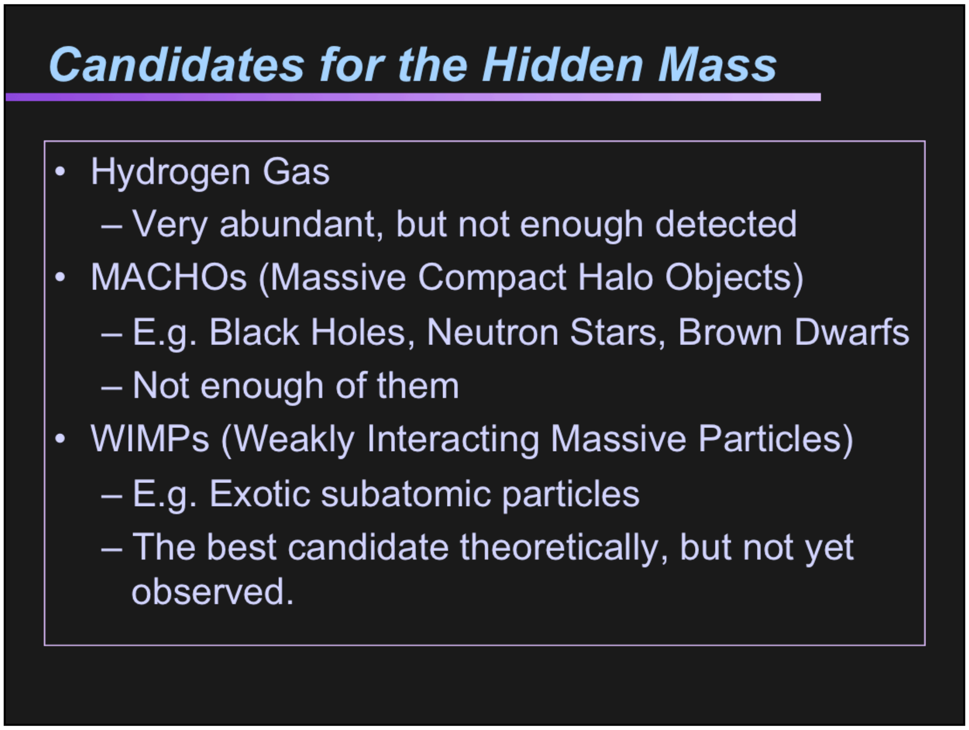
There *must* be Missing Mass!!



From observations of hot gas in galaxies and data from the Rotation Curves, we conclude that gas and stars in galaxies are moving faster than what we would expect from the visible mass of the galaxy. Note that by "visible", we mean here mass detected at all wavelengths of the e-m spectrum, and not just optical.

We find that only 10 % of the mass of the galaxy is detectable.

WMAP results from Feb 2003 show that 4% of the universe is ordinary matter, 235 is cold dark matter, and 73% is dark energy.

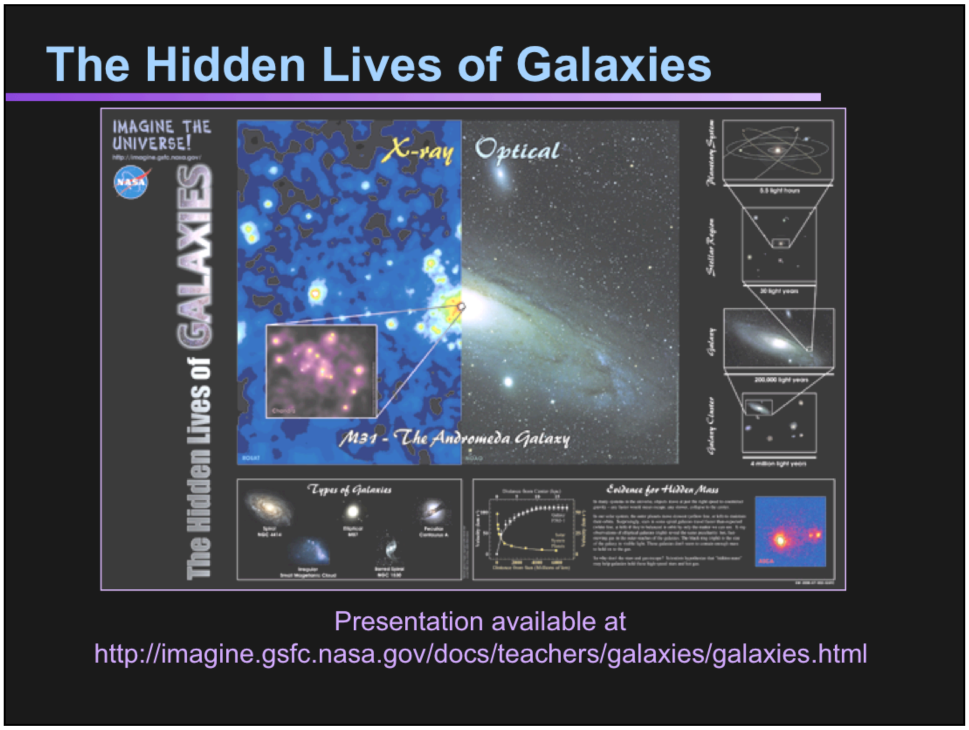


Scientists have various candidates for what the hidden mass in galaxies could be.

Hydrogen gas is abundant in galaxies, but there is still not enough of it.

Massive Compact Halo Objects are objects such as black holes, neutron stars and brown dwarfs. Again, there just aren't enough of them.

The best candidate is Weakly Interacting Massive Particles. These are as yet undiscovered sub-atomic particles that interact weakly with normal matter but yet have mass. This is currently a very active field of particle physics and cosmology.



In this presentation, we'll discuss the information about galaxies contained in "The Hidden Lives of Galaxies" poster and information booklet. We'll also do a couple of classroom activities discussed in the booklet

This version of the presentation includes information on galaxy formation, and has expanded approach for determining that galaxies have hidden mass

[An image of the poster and text of the booklet are available on-line at http://imagine.gsfc.nasa.gov/docs/teachers/galaxies/galaxies.html]