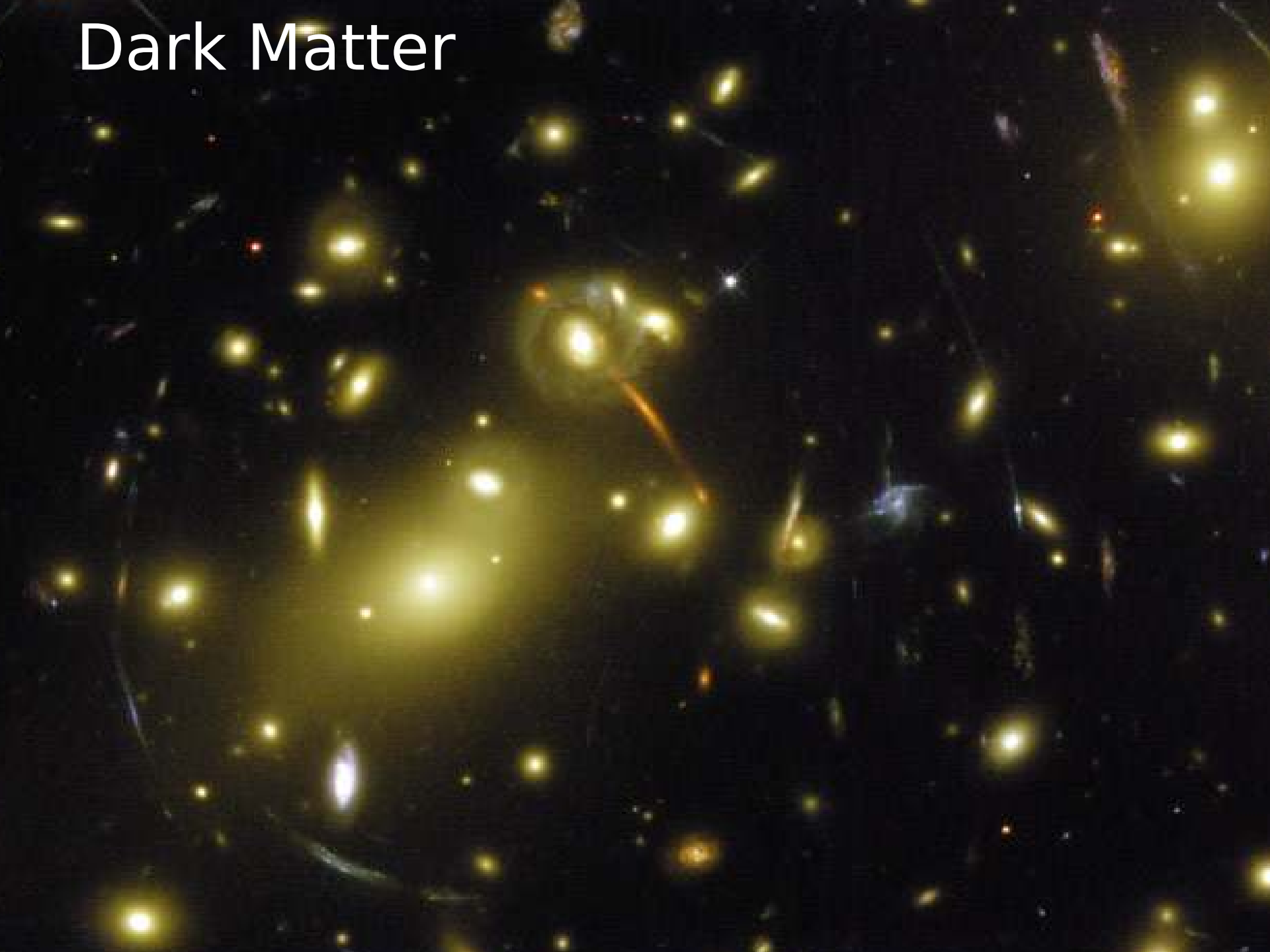


Dark Matter



Orbits, mass, and radius

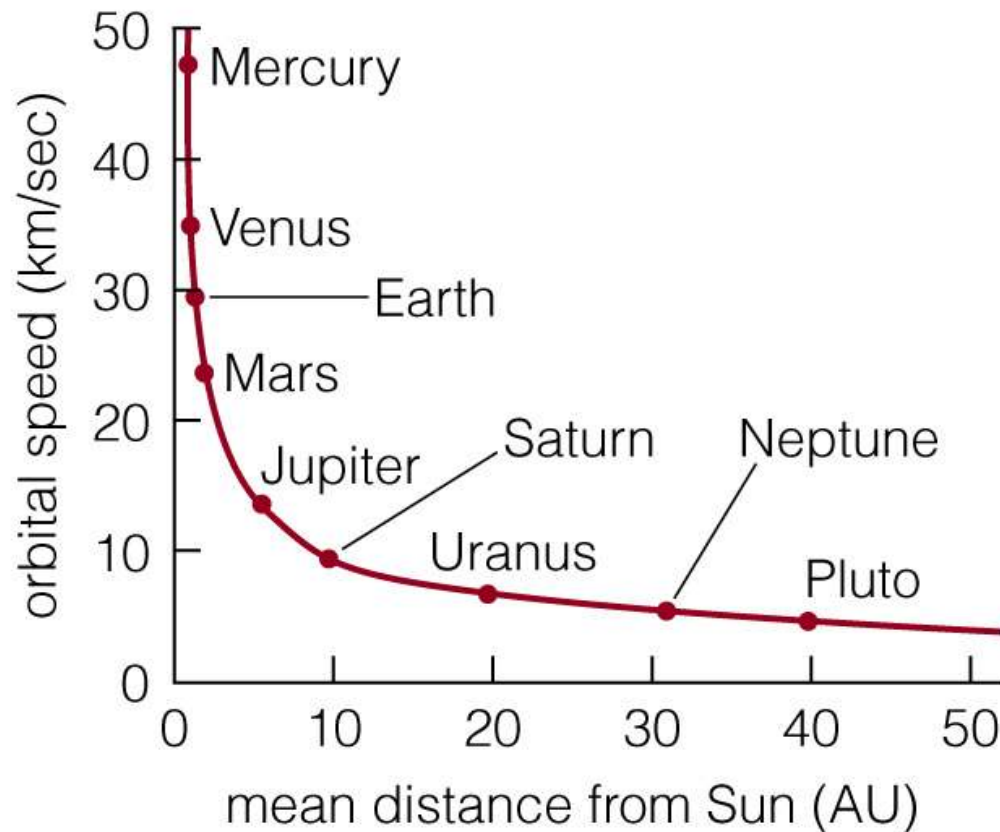
Orbital speed is related to the mass interior to the orbit, and the orbital radius

http://boojum.as.arizona.edu/~jill/NS102_2004/Lectures/SystemFiles/ToolBrowser/Tutorial_15/orbital_velocity_mass_and_r.swf

LT Book

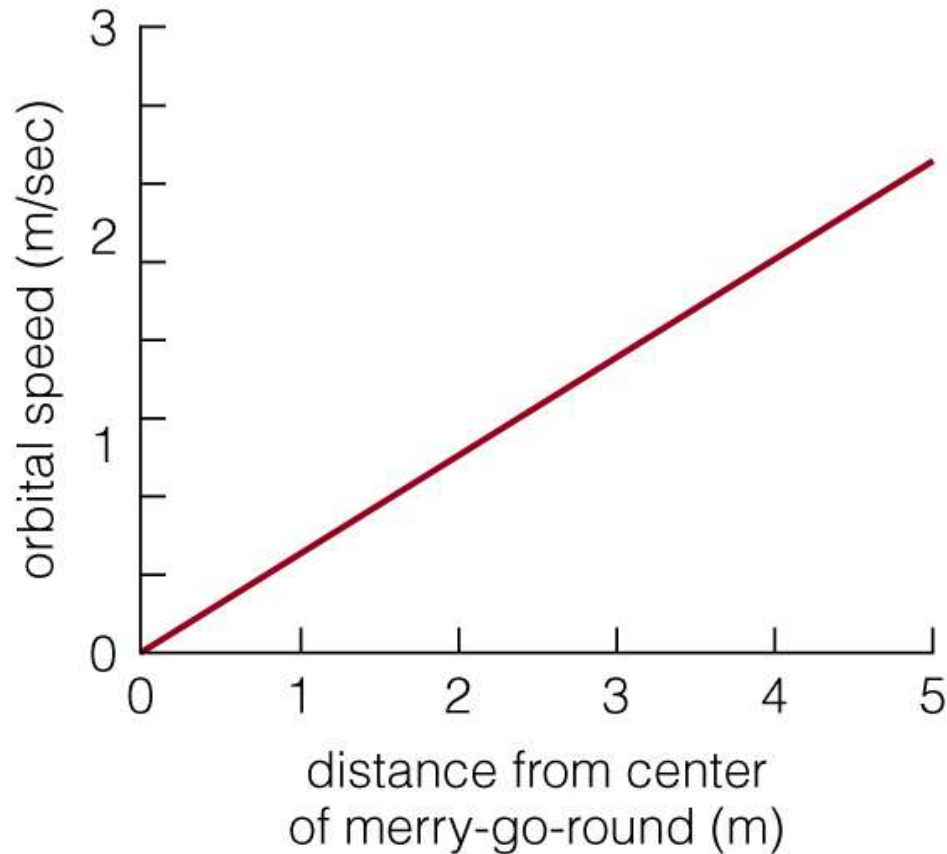
“Dark Matter,” 143, #1-9

Solar System Rotation Curve



- Solar system's rotation curve declines because Sun has almost all the mass
- This is what is expected from Kepler's 3rd law

Merry-go-round Rotation Curve

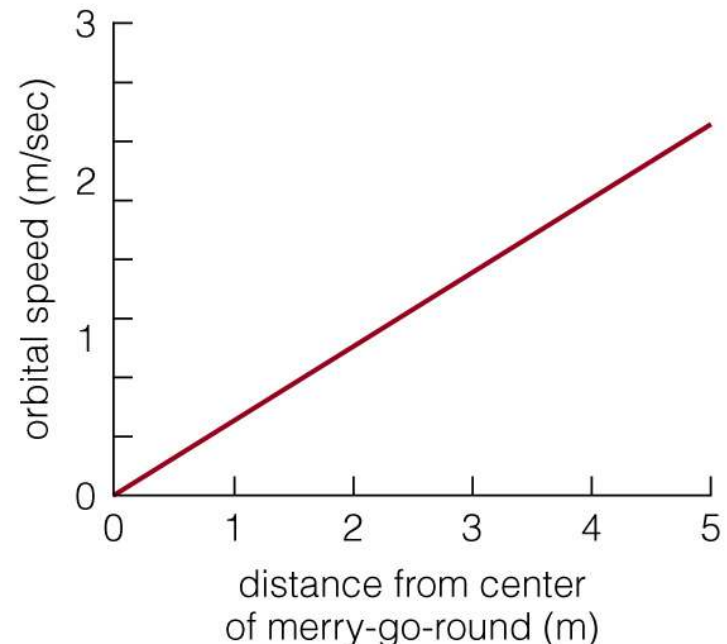
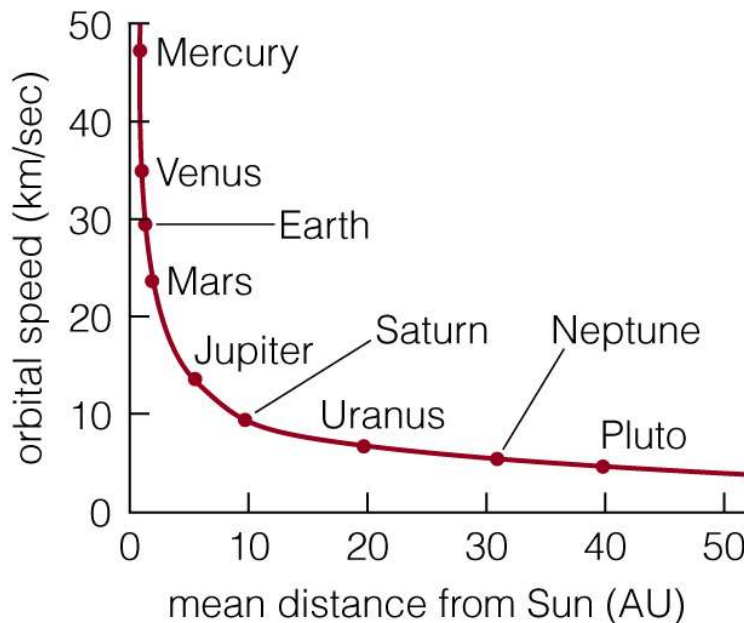


Rotation curve of merry-go-round rises with radius because mass is spread out with radius

Concept Quiz

What will the rotation curve of our Galaxy look like?

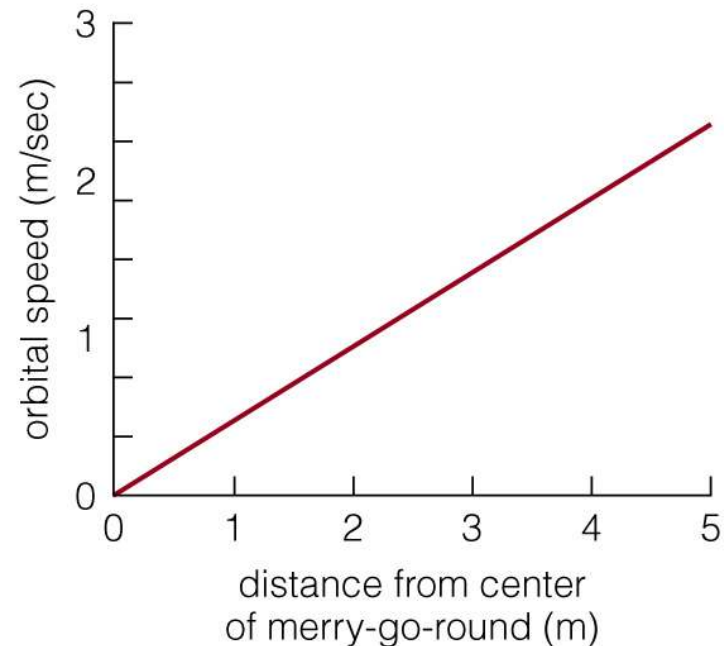
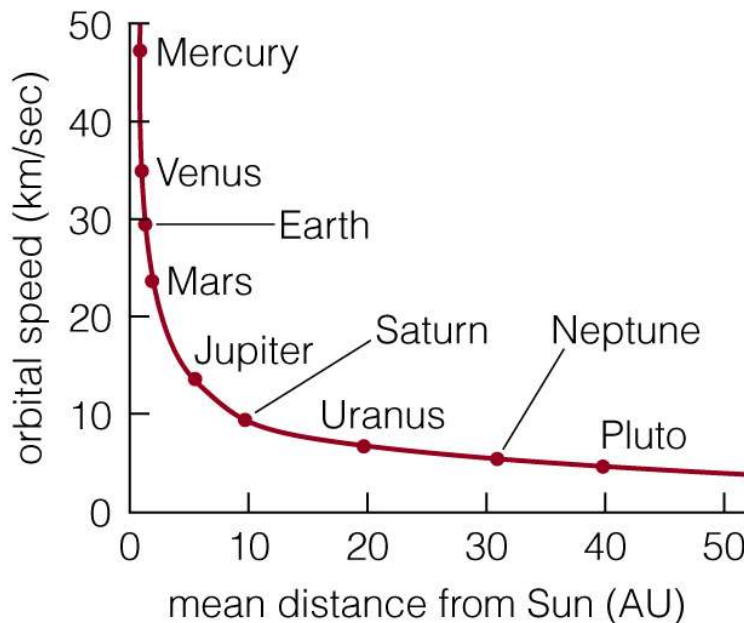
- A) Like that of the Solar System
- B) Like that of the Merry-go-round



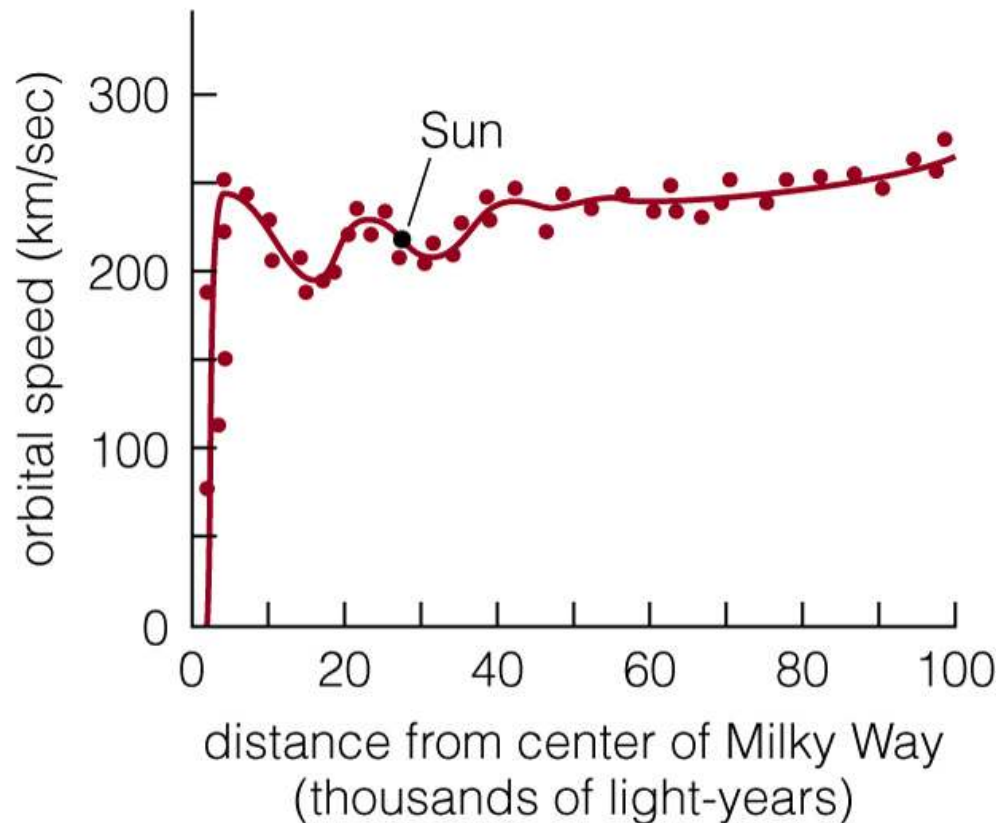
Concept Quiz

What will the rotation curve of our Galaxy look like?

- A) Like that of the Solar System
- B) Like that of the Merry-go-round
- C) Neither! Ha!

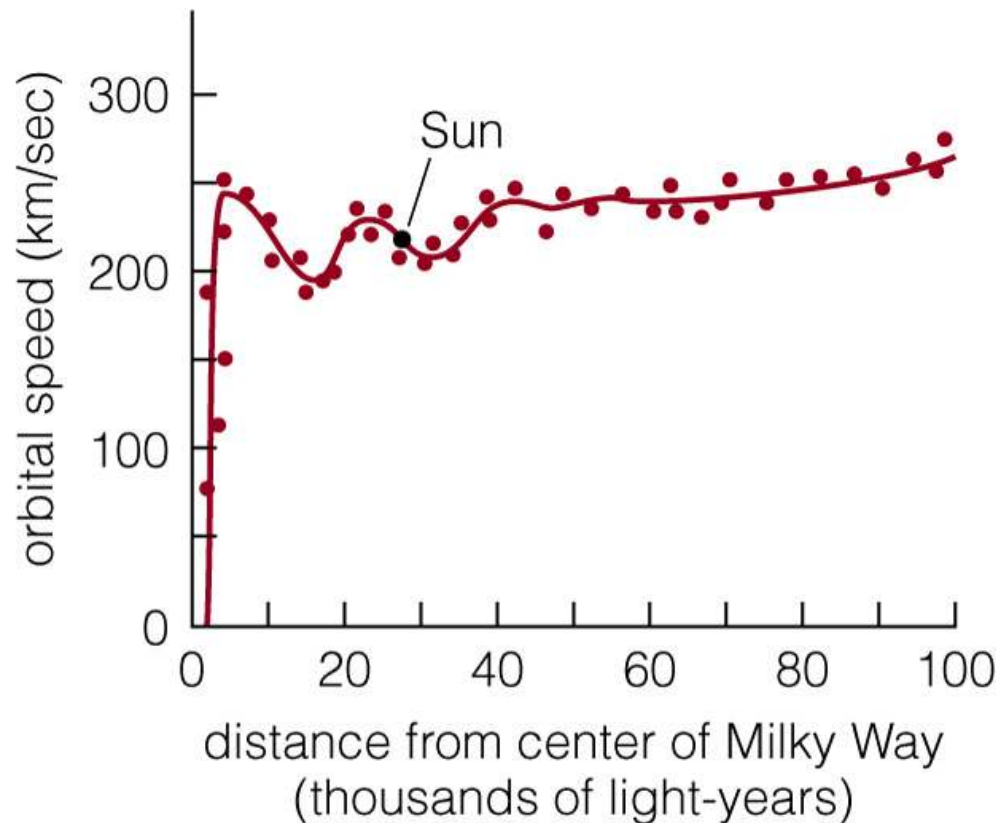


Milky Way Rotation Curve



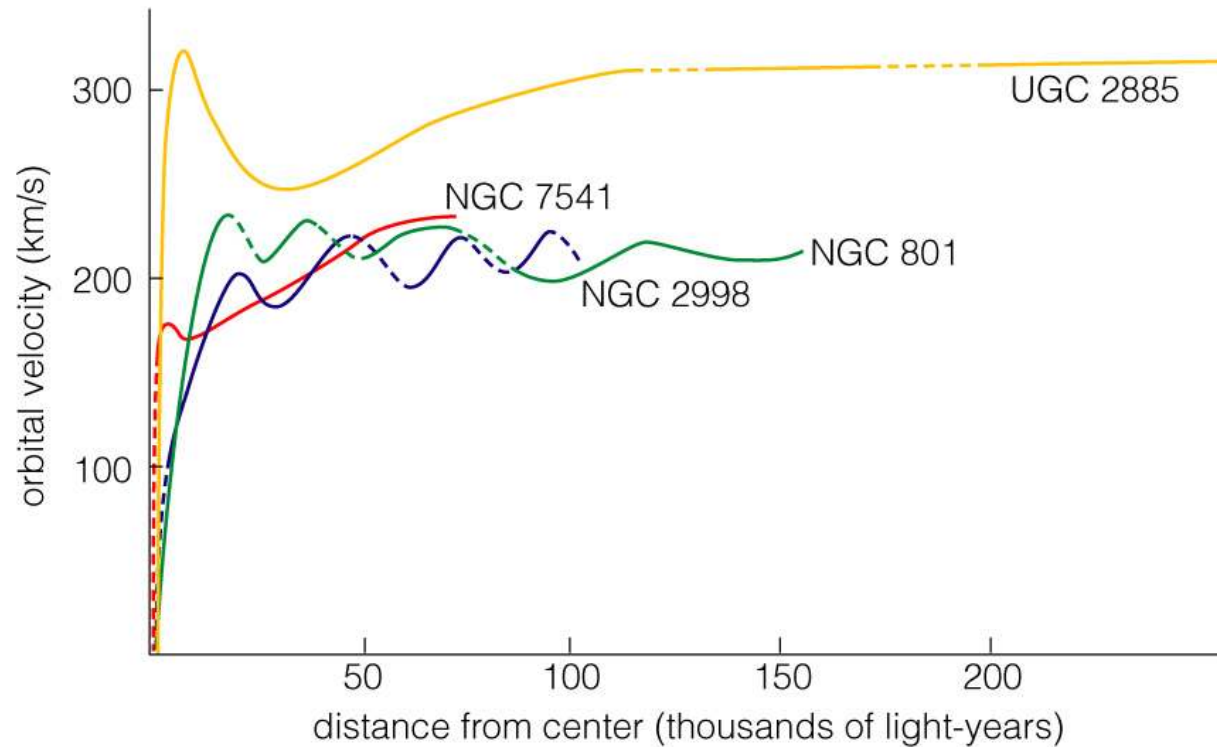
Mass must be more spread out than in solar system, but not as much as for a merry-go-round

Milky Way Rotation Curve



But from visible matter, we would expect something more like what we see in the Solar System because most of the mass is in the center of the Galaxy.

Dark Matter in Spirals



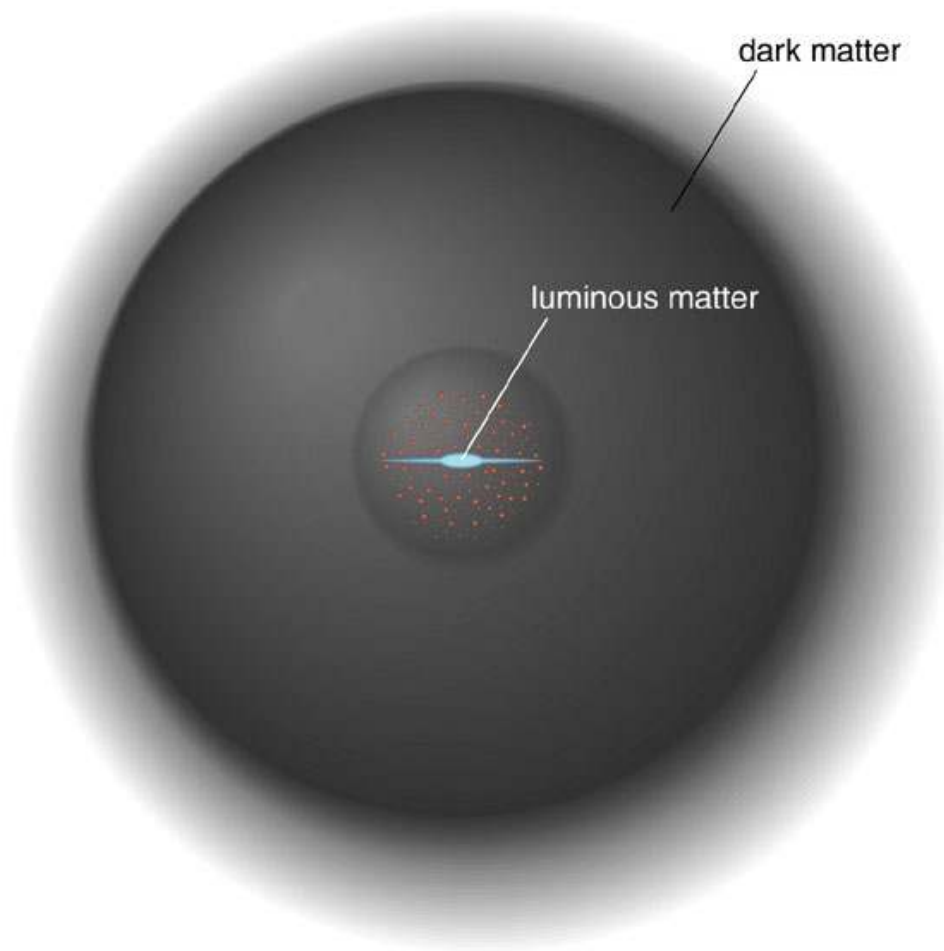
- Spiral galaxies all tend to have flat rotation curves
- -> Lots of Dark Matter!
- Ellipticals have dark matter too, but they don't have rotation curves

Evidence for Dark Matter

We hypothesize that dark matter exists from comparisons between the mass of the matter we can see and the mass calculated from gravity

We'll see two forms of evidence for dark matter – in galaxies and in clusters

Dark Matter



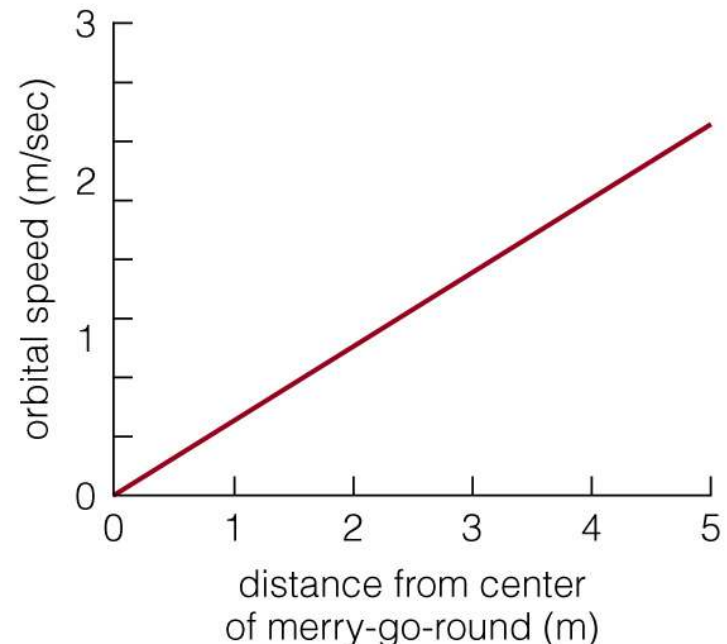
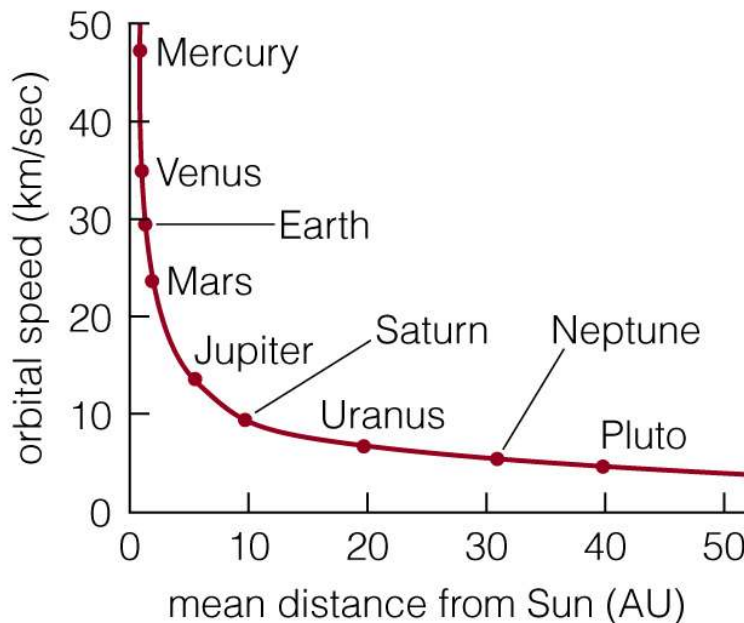
The visible portion of a galaxy lies deep in the heart of a large halo of dark matter

Dark Matter provides the missing mass

Concept Quiz

What will the rotation curve of our Galaxy look like?

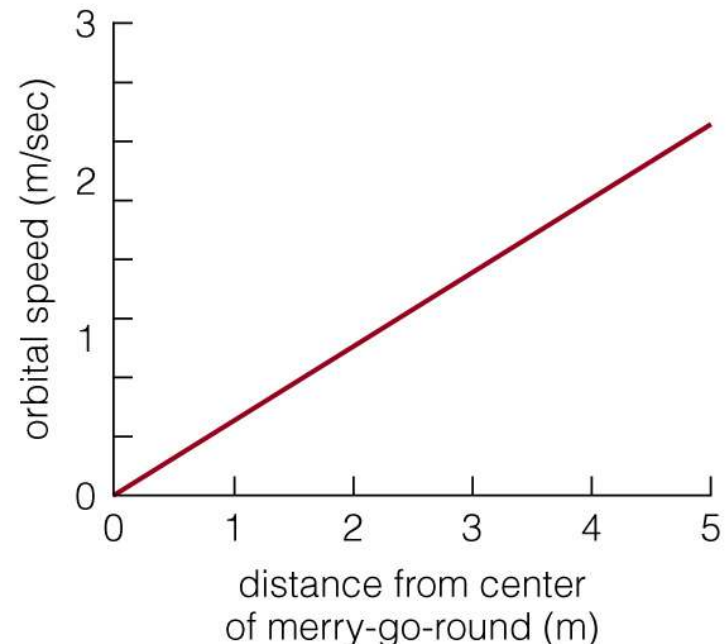
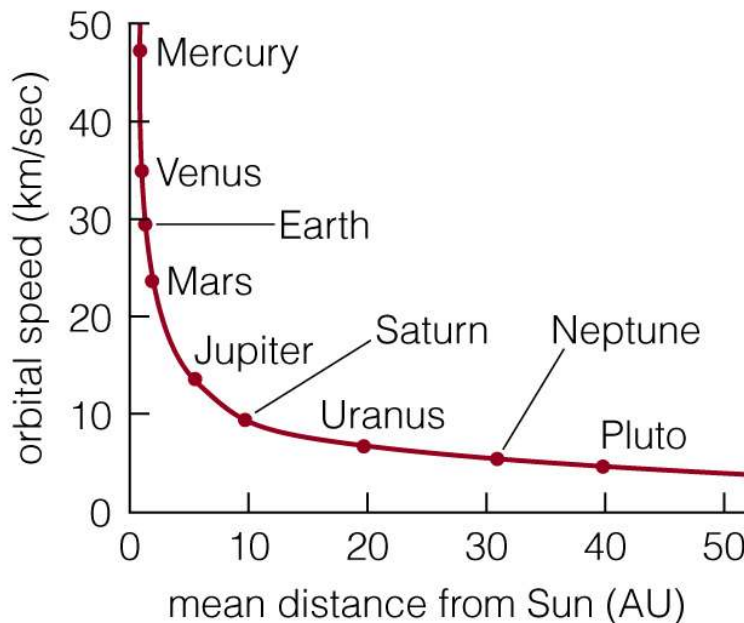
- A) Like that of the Solar System
- B) Like that of the Merry-go-round



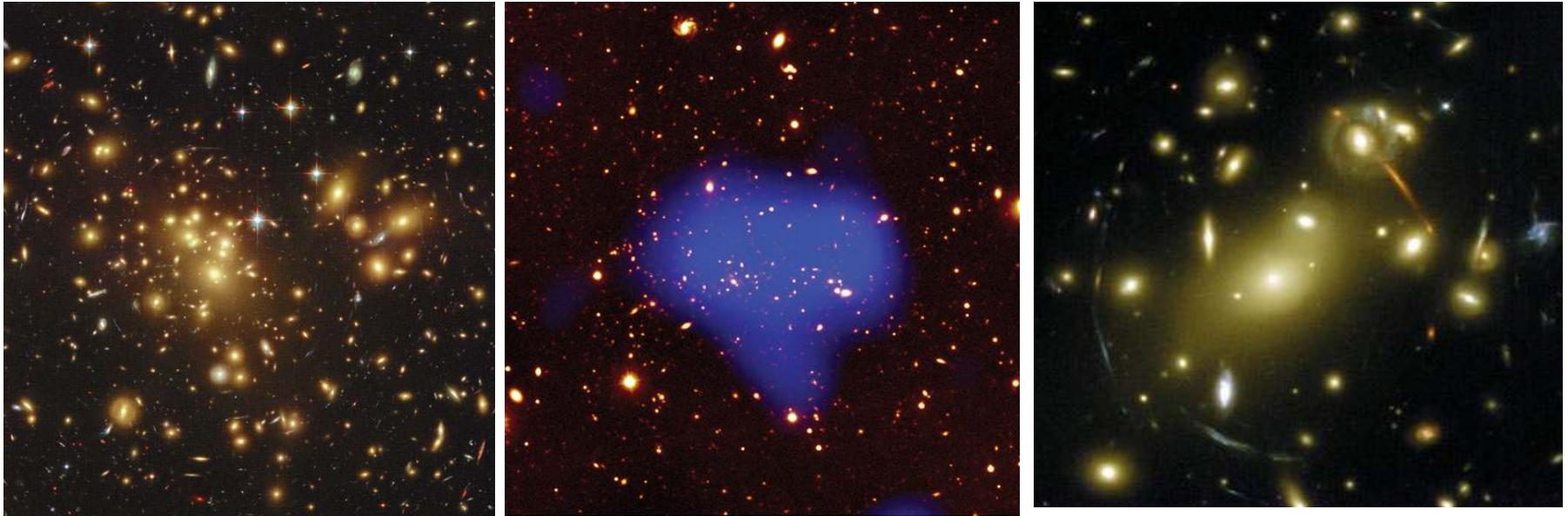
Concept Quiz

What will the rotation curve of our Galaxy look like?

- A) Like that of the Solar System
- B) Like that of the Merry-go-round

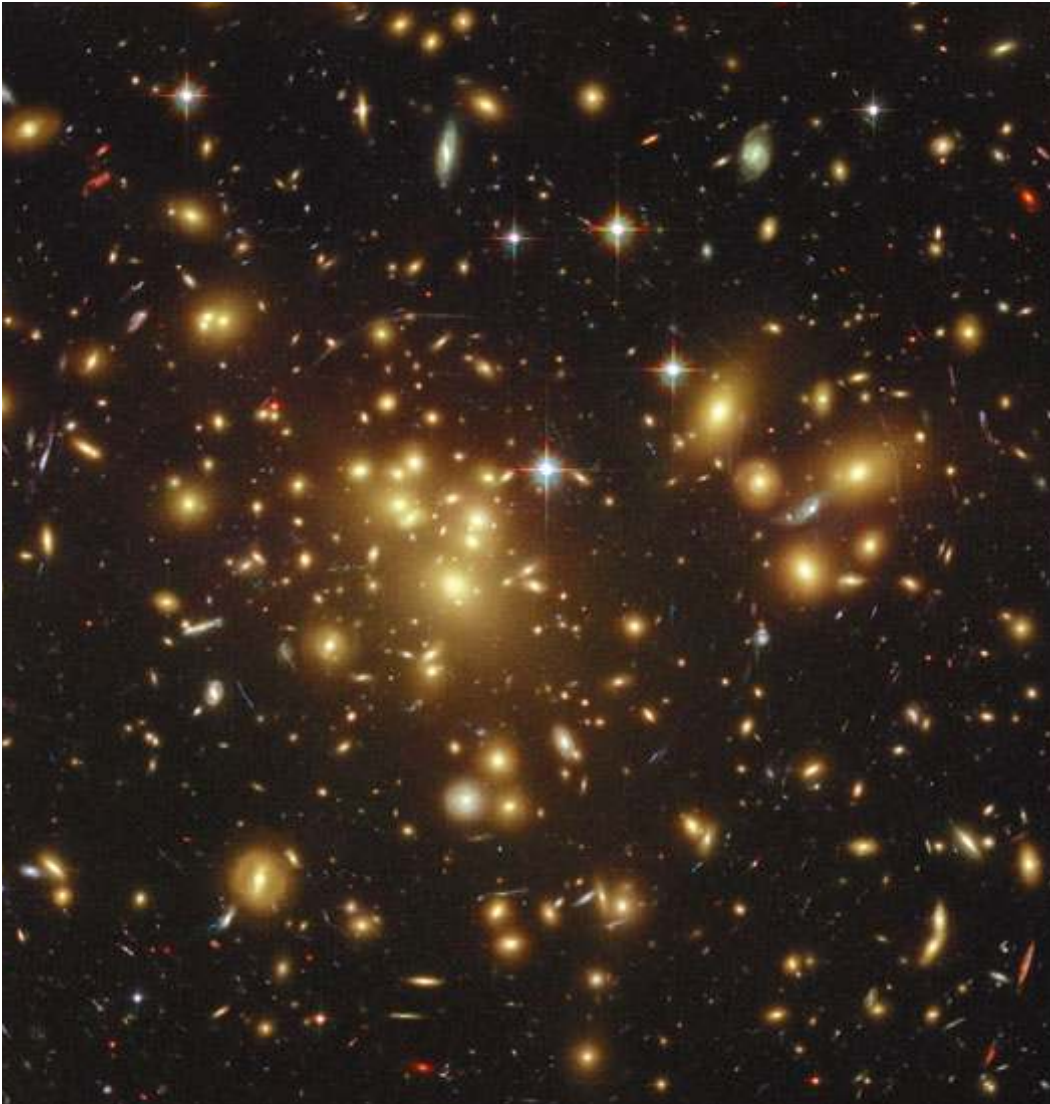


Dark Matter in Clusters



Clusters are large groups of galaxies
There are three ways to find cluster
mass

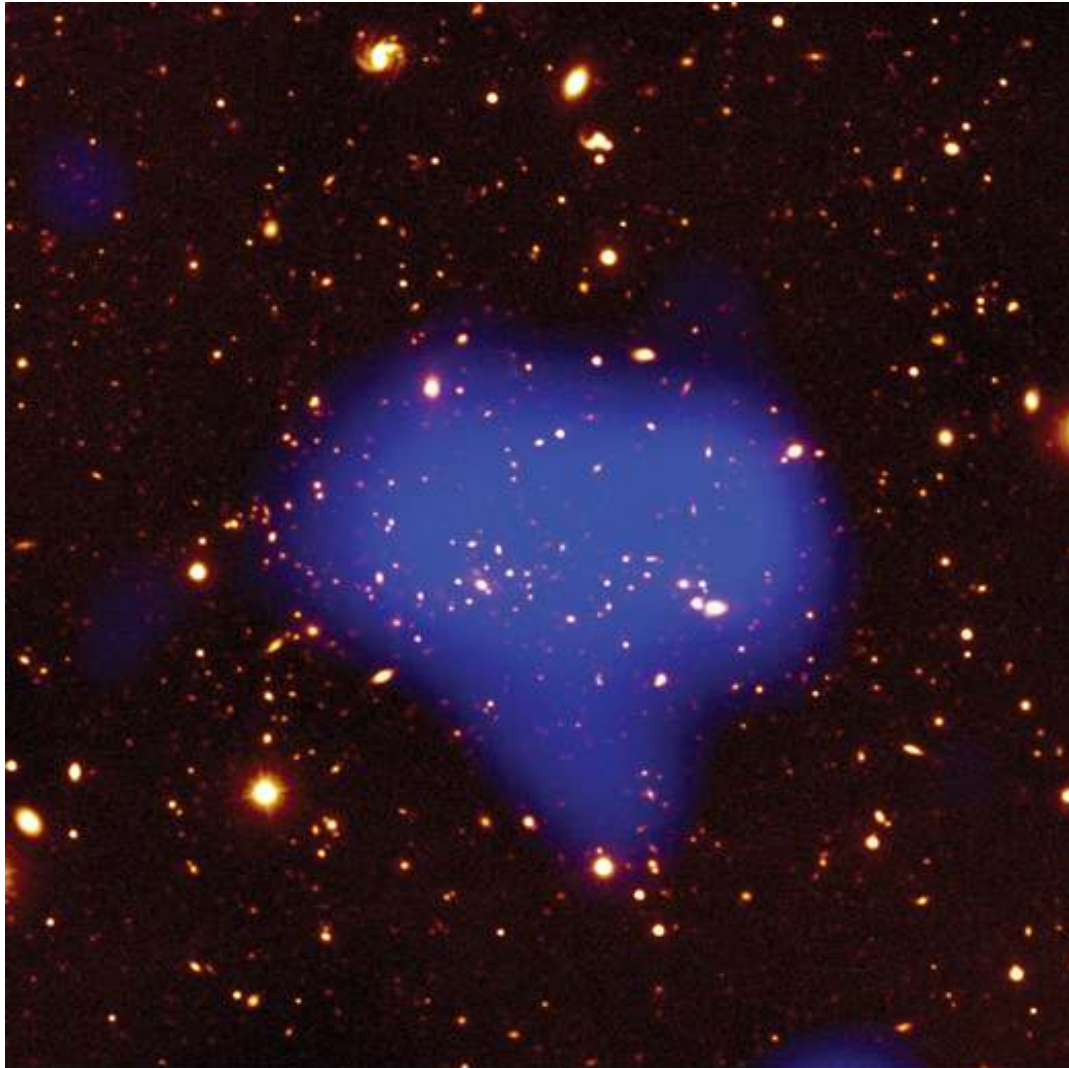
1) Velocities of galaxies



The galaxies are moving too fast, indicating unseen mass

The mass we calculate from galaxy motions in a cluster is about ***50 times*** larger than the mass in stars!

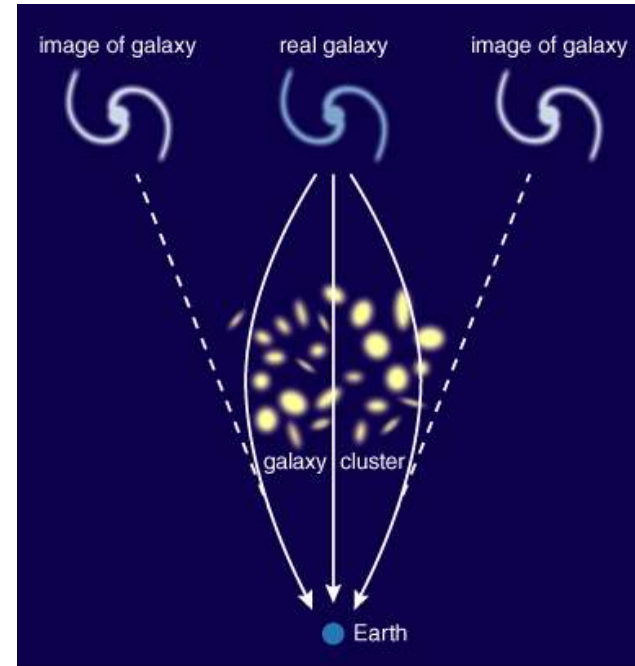
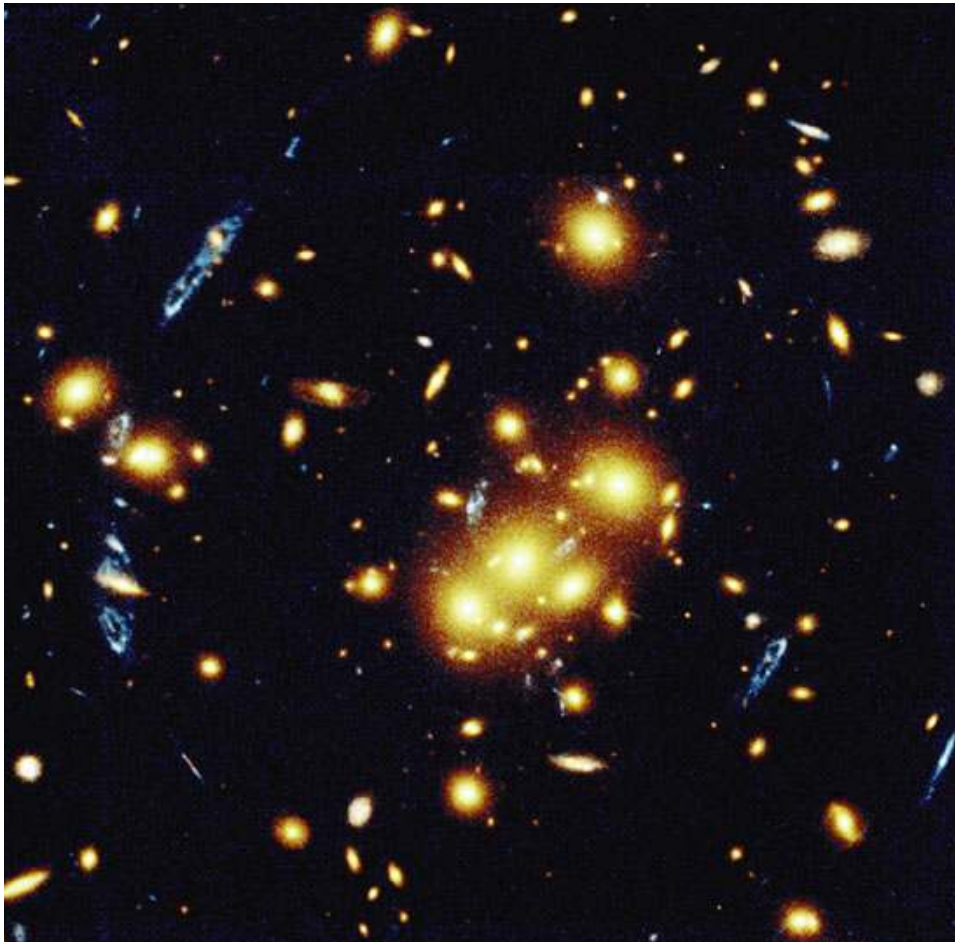
2) Mass traced through X-rays



Clusters contain large amounts of X-ray emitting hot gas

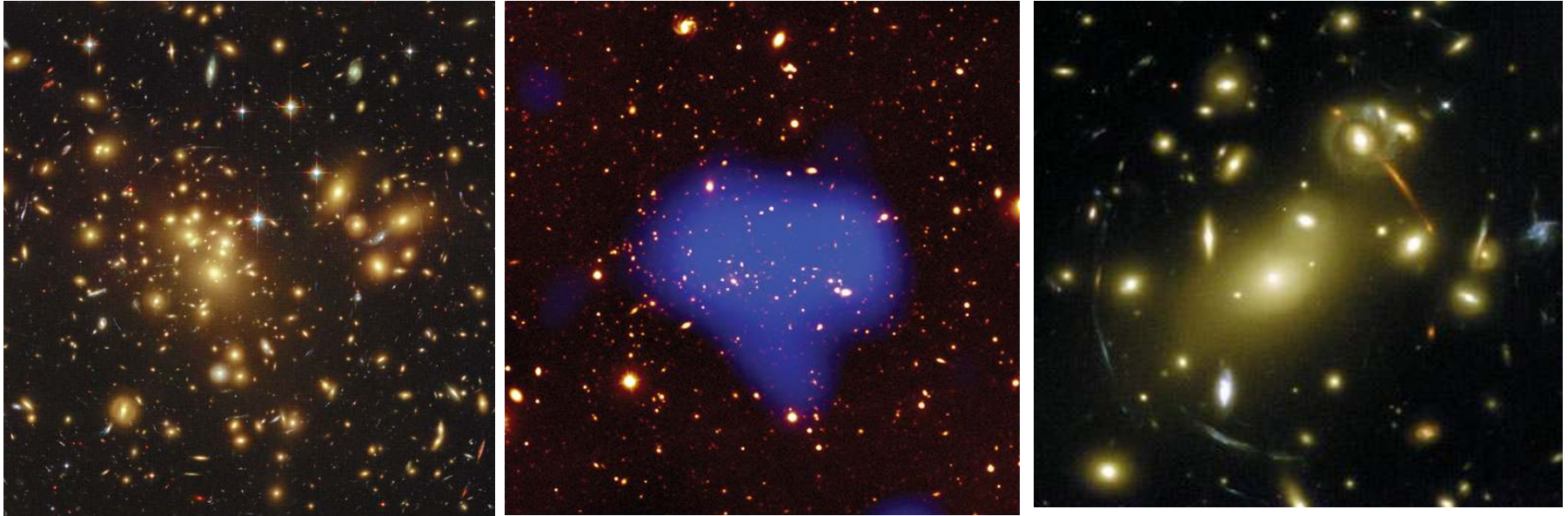
Temperature of hot gas (particle motions) tells us cluster mass. The gas is hotter than it would be if there was no dark matter.

3) Gravitational Lensing



Gravitational lensing, the bending of light rays by gravity, can also tell us a cluster's mass

Cluster Masses



All three methods of measuring cluster mass indicate similar amounts of dark matter

But Does Dark Matter Really Exist???

Something is needed to explain the discrepancy between the mass measured through gravity and the mass directly observed.

- 1) Dark matter really exists, and we are observing the effects of its gravitational attraction
- 2) Something is wrong with our understanding of gravity, causing us to mistakenly infer the existence of dark matter

Because gravity is so well tested, most (but not all!) astronomers prefer option #1

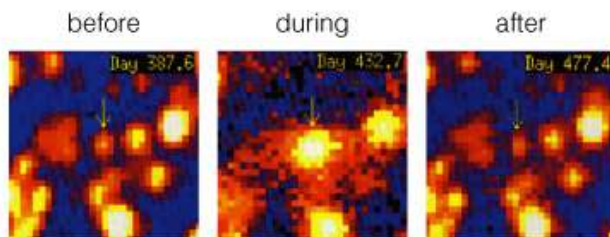
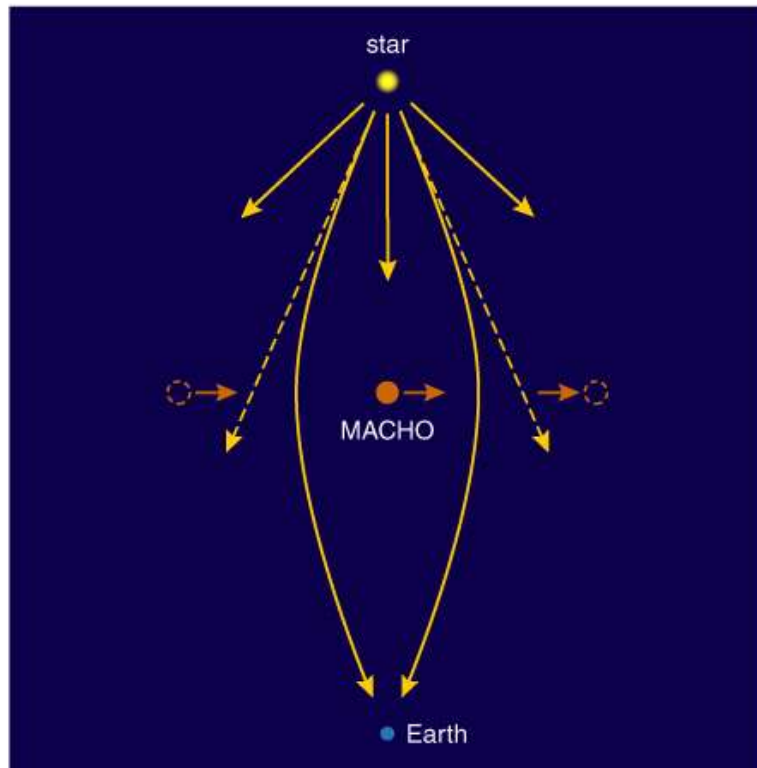
How dark is dark matter?

... not as bright as a star.

Two Basic Options

- Ordinary Dark Matter (MACHOS)
 - Massive Compact Halo Objects:
dead or failed stars in halos of galaxies –
basically brown dwarfs
- Extraordinary Dark Matter (WIMPS)
 - Weakly Interacting Massive Particles:
a new type of particle – possibly similar
to a neutrino

Evidence for MACHOS



MACHOs
occasionally make
other stars appear
brighter through
lensing

... but there are
not enough
lensing events to
explain all the
dark matter

Evidence for WIMPs

- There's not enough ordinary matter
- WIMPs could be left over from Big Bang
- Models involving WIMPs explain how galaxy formation works

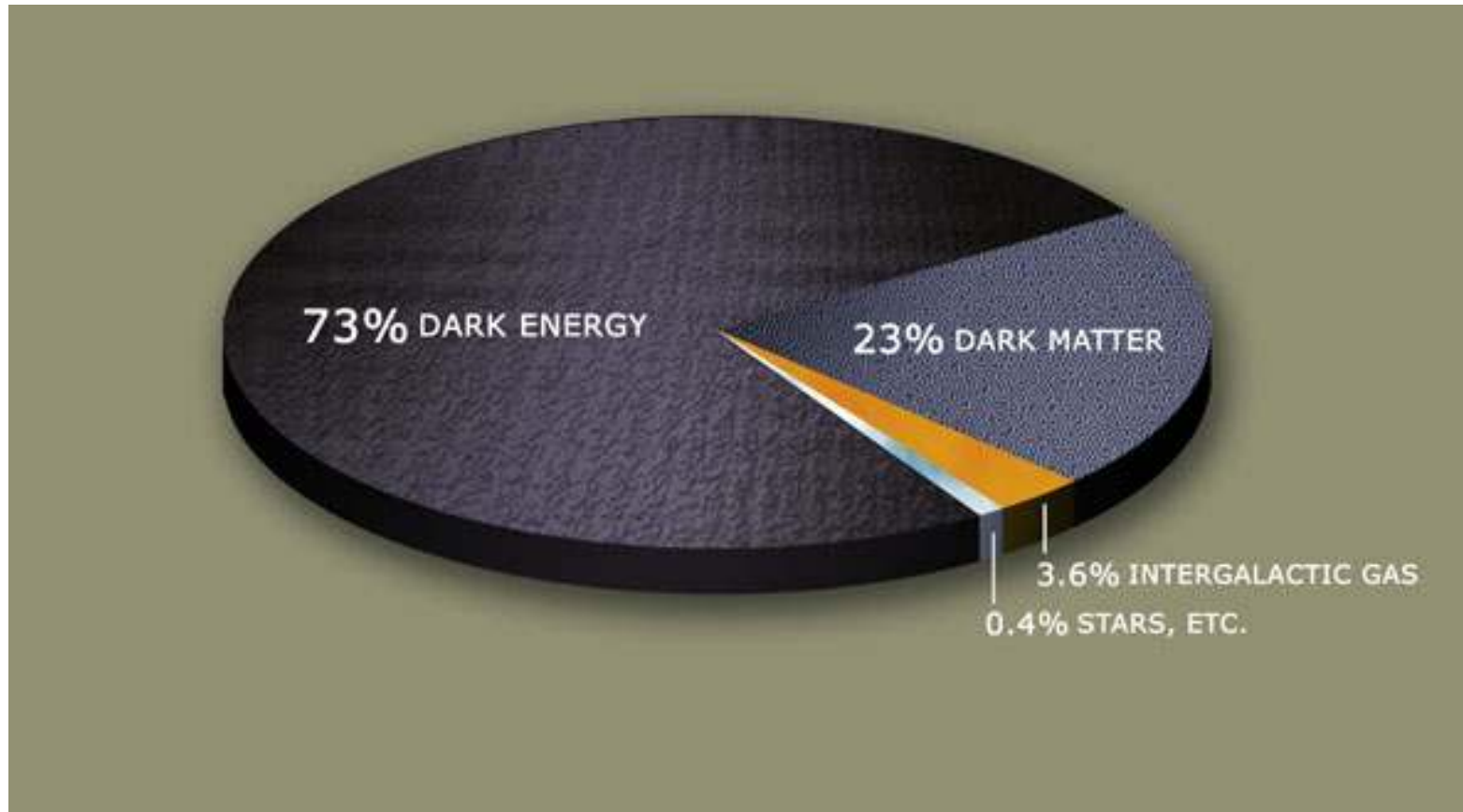
Unseen Influences

Dark Matter: An undetected form of mass that does not emit light but whose existence we infer from its gravitational influence

Dark Energy: An unknown form of energy that seems to be the source of a repulsive force causing the expansion of the universe to accelerate

Contents of Universe

“Normal” Matter: $\sim 4\%$
Dark Matter: $\sim 23\%$
Dark Energy $\sim 73\%$



Contents of the Universe

The energy of the Universe is roughly $\frac{2}{3}$ dark energy and $\frac{1}{3}$ matter

Of the matter, about 10% is normal matter (protons, neutrons) and 90% is dark matter

We can see only 4% of the energy of the Universe

– We cannot see most of what makes up the Universe!

What have we learned?

1) What are dark matter and dark energy?

- “Dark matter” is the name given to the unseen mass whose gravity governs the observed motions of stars and gas clouds
- “Dark energy” is the name given to whatever might be causing the expansion of the universe to accelerate

2) What is the evidence for dark matter in galaxies?

- Rotation curves of galaxies are flat, indicating that most of their matter lies outside their visible regions

3) What is the evidence for dark matter in clusters of galaxies?

Masses measured from galaxy motions, temperature of hot gas, and gravitational lensing all indicate that the vast majority of matter in clusters is dark

4) What might dark matter be made of?

There does not seem to be enough normal matter to account for all the dark matter, so most astronomers suspect that dark matter is made of particles that have not yet been discovered